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COMPARISION OF EMP AND HERO PROGRAMS

by

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December 1988

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Because of the unique features of electromagnetic pulse (EMP) and Hazardous Electromagnetic Effects on Ordnance (HERO), much research and money has gone into protecting weapon systems and ordnance against it. The EMP and HERO phenomena do have a variety of differences and require differences of hardening technique to protect against it. However, they both involve radiation effects and can prematurely initiate ordnance via the electroexplosive device (EED). Protection of weapon systems and ordnance against electronic damage and upset plus EED initiation takes on more of an art form rather than science once basic principles are applied. Nevertheless by relating these two programs via the initiating temperature of the EED, they can be accurately compared with each other. Because of this observation, the two programs can be effectively combined to work jointly on ordnance hardening and protection including all forms of radiation type hazards, present and future.

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COMPARISION OF EMP AND HERO PROGRAMS

by

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ABSTRACT

Because of the unique features of electromagnetic pulse (EMP) and Hazardous Electromagnetic Effects on Ordnance (HERO), much research and money has gone into protecting weapon systems and ordnance against it. The EMP and HERO phenomena do have a variety of differences and require differences of hardening technique to protect against it. However, they both involve radiation effects and can prematurely initiate ordnance via the electroexplosive device (EED). Protection of weapon systems and ordnance against electronic damage and upset plus EED initiation takes on more of an art form rather than science once basic principles are applied. Nevertheless by relating these two programs via the initiating temperature of the EED, they can be accurately compared with each other. Because of this observation, the two programs can be effectively combined to work jointly on ordnance hardening and protection including all forms of radiation type hazards, present and future.

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ACRONYMS

ACRONYM	DEFINITION
ac	Alternating Current
ASTM	American Society of Testing Materials
C	Chemical
CBE	Carbon Bridge EED
cm	Centimeter
CME	Conductive Mix EED
CW	Continuous Wave
dB	Decibel
DBT	Deposited Bridge Transducers
dc	Direct Current
DNA	Defense Nuclear Agency
DRI	Denver Research Institute
DTI	Determine the Test Interval
EAC	Establish the Acceptance (or Failure) Criteria
EBW	Exploding Bridgewire
EC	Electrostatic Discharge
ECC	Electrical Connected Circuitry
ECEMP	Electron Caused EMP
EED	Electroexplosive Device
EHM	EMP Hardness Margin
EMC	Electromagnetic Compatibility
EMCAB	Electromagnetic Compatibility Advisory Board
EMCON	Emission Control
EME	Electromagnetic Environment
EMFI	Electromagnetic Field Intensity
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EMR	Electromagnetic Radiation

EMRH	Electromagnetic Radiation Hazard
EMRO	Electromagnetic Radiation Operation
EMV	Electromagnetic Vulnerability
EMW	Electromagnetic Wave
ESA	Electric Surge Arrester
Fe	Iron
fm	Frequency Modulation
FOM	Figure of Merit
FTM	Fourier Transform Method
GHz	Gigahertz
H	Heat
HBW	Hot Bridgewire
HE	High Explosive
HERF	Hazards of Electromagnetic Radiation to Fuels
HERO	Hazards of Electromagnetic Radiation to Ordnance
HERP	Hazards of Electromagnetic Radiation to Personnel
HF	High Frequency
IEMP	Internal EMP
IR	Infrared
kMc	Kilomegacycles
kW	Kilowatts
LCC	Life Cycle Cost
LF	Low Frequency
ln	Natural Log
LPN	Lumped Parameter Nonlinear
M	Mechanical
ma	Milliampere
MAE	Maximum Allowable Environment
MDC	Maximum Detectable Current
MF	Medium Frequency
MHz	Megahertz
MK	Mark

mm	Millimeter
MNFC	Maximum No-Fire Current
MNFE	Maximum No-Fire Energy
MNFP	Maximum No-Fire Power
MNFS	Maximum No-Fire Stimulus
MNFV	Maximum No-Fire Voltage
mW	Milliwatt
MW	Megawatt
NADC/J	Naval Air Development Center Johnsville
NAVORD	Naval Ordnance
NAVSEA	Naval Sea Systems Command
NAVSEAINST	Naval Sea Systems Command Instruction
Ni	Nickel
NOL/C	Naval Ordnance Laboratory, Corona, CA
NOL/WO	Naval Ordnance Laboratory, White Oak, MD
NOTS	Naval Ordnance Test Station
NSWC	Naval Surface Warfare Center
NWL	Naval Weapons Laboratory
rad	Measurement of radiation in joules per second per gram
Radar	Radio Detection and Range
RADHAZ	Radiation Hazards
RF	Radio Frequency
SGEMP	System Generated EMP
sinh	hyperbolic sine
SOP	Standard Operating Procedure
sqrt	square root
SREMP	Source Region EMP
SSL	Select the Stress Level
TEM	Transverse Electromagnetic
TPC	Transient Protected Connector
TPD	Terminal Protection Device
UHF	Ultra High Frequency

V/M	Volt per Meter
VHF	Very High Frequency
VLF	Very Low Frequency
W	Watt

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I. INTRODUCTION

Since the early 1800's it has been discovered that electromagnetic waves can produce current in wires. In the early 1960's this knowledge resulted in the formation of the Hazards of Electromagnetic Radiation to Ordnance (HERO) program and the Electromagnetic Vulnerability (EMV) program to protect naval ordnance and weapon systems from premature detonation. Also in the early 1960's it was discovered that an Electromagnetic Pulse from a high altitude nuclear explosion could prematurely detonate ordnance and weapon systems as well. But, it was not until the 1980's that an EMP program receive full recognition and support.

The HERO program has extensively tested the detonating devices called Electroexplosive devices (EED's) which heat up and initiate the detonation via current flow. The HERO program also has developed very skilled and creative hardening designs for those ordnance and weapon systems containing EED's. The problem is how much HERO data can be used by the relatively new EMP program? Can the HERO data on EED current firing be transformed to reflect an EMP or are each phenomena so different that comparisons of data are futile? Would there be any major or minor changes in the hardening design for EMP hardening of a weapon system versus what would be necessary to ensure HERO safety? Are there reliable equations that can accurately relate the different radiation phenomena (i.e., EMP and HERO) to actual initiation or detonation? Is there in turn a transfer function to bridge the gap totally from EMP to HERO and vice versa?

By carefully and thoughtly studying each phenomena and by carefully reviewing hardening against electromagnetic radiation, it is hoped that some common areas between the two phenomena might surface. These common areas can be built upon by investigating the mechanism of initiation or detonation under a variety of conditions thus including EMP and HERO type conditions. Because the EED's are thermally ignited, it is feasible to include heat flow dynamics as well as fundamental electromagnetic theory. By combining these two disciplines the problem should be able to be solved.

If it is possible for data to be shared among the two programs and that data can be used to interpret its own effects, then valuable resources and time can be saved in forming EMP standards for the fleet. Also it will be possible for both programs to

effectively combine resources and cover all electromagnetic radiation hazards jointly and set a single design standard for the hardening of ordnance or weapon systems. In addition it would be possible to cover other transient outside the purview of either program at opposite ends of the time and power spectrum.

By covering EMP and HERO first the reader is introduced into the phenomena with a little historical background to gain a perspective. The chapter on Hardening covers techniques as well as design of hardening and many of the common elements in the two programs become clear. After briefly discussing the EED and the testing methods for each program, the Analysis chapter serves to not only introduce the heat flow dynamics but link it up with electromagnetic theory. This linking of the two disciplines is represented in the transfer function. The transfer functions show how an EMP or electromagnetic radiation generated from antenna power source can be converted into a current function which in turn results in ohmic heating for initiation.

II. ELECTROMAGNETIC PULSE (EMP)

A. EMP GENERATION

1. Introduction

As seen in appendix A EMP generated by a nuclear explosion has been of interest since 1945. It was not until the early 1960's that hardening of military systems became an open concern. Also it was in the early 1960's that high altitude EMP burst mechanisms were understood. Since that time simulators and computer coded simulations have aided scientists in understanding the EMP.

When there is a high altitude burst, the emitted x-rays and gamma rays produce no fireball because of the low air density. Also, because of the low density atmosphere the photons travel much farther than at lower altitudes. The photon source region can be up to 20 miles thick and 100 miles in diameter. As seen in Figure 5 on page 94 and Figure 6 on page 95, these photons can ionize a significant portion of the atmosphere potentially covering the entire United States and consequently generating an electromagnetic pulse (EMP).

Since conventional explosives can generate electromagnetic signals after explosion, it was predicted that nuclear explosives would generate an electromagnetic pulse (EMP). However, the dangers of this EMP were not predicted. It was not until the early 1950's that the malfunction failure of equipment could be attributed to the EMP. In 1960 the potential hazards of EMP were recognized as well as possible benefits such as long range detection of nuclear detonations. When above ground detonation of nuclear weapons were being performed in the 1960's, some data concerning EMP was collected. Since this time, below ground detonation , simulators, and computer simulations have provided most of the information concerning EMP.

In essence, nuclear EMP is no different than any propagating electromagnetic wave radiation. However, in the EMP there is a very rapid rise to peak current amplitude on the order of a microsecond and up to 50,000 volts per meter. There is a subsequent slow decay. The frequency range of the radiation is very broad, from two up to 100 megahertz. [Ref. 1]

2. Nature and Characteristics of EMP

The strength of the electromagnetic field being radiated is very large but short lived. As the radiation travels at the speed of light conductors pick up this radiation and

induce currents in them. Obviously the weapon yield and height of burst dictate the parameters of EMP.

In comparing EMP and lightning, there have been a number of similar qualities involving use of shielded enclosures, shielding cables, terminal protection, and controlled grounds. There are however three areas of difference to note which are:

- Depending on lightning ground for EMP protection
- Integrating EMP and lightning terminal protection
- Combating EMP effects on unique circuits developed for lightning protection. [Ref. 1]

The shields for lightning may be functional against the low frequency of the EMP, but may not against the high frequency. The faster rise time of the EMP results in a broader energy spectrum. The EMP is less localized than the lightning and induces high potential differences whereas the lightning produces high current densities.

3. Fundamentals of Electromagnetic theory

Upon detonation of a nuclear weapon in the atmosphere, the dominant photon interaction is Compton scattering with the photons having high enough energy to repeat the Compton process. The free electrons produced travel away from the burst point creating an electron current. Being that the velocity of electrons is greater than the velocity of the positive ions, there is a partial charge separation and therefore a radial electric field. The gamma ray pulse which generates the Compton scattering peaks in less than one microsecond. As the photons move outward, lower energy free electrons are generated. These electrons are attracted back toward the burst point because of the charge separation. This creates a conduction current. The force on the electrons, thus the magnitude of the current increases as the Compton current increases. Since the direction of the conduction current is opposite to the direction of the Compton current, there is a point when the electric field ceases to increase. This point is called ***saturation***. Obviously saturation occurs sooner near the burst point. If the gamma rays coming from the burst point form a homogenous uniform circle, then the electric field will be limited to the area of charge separation and the rays will ionize the medium and the energy will be degraded into thermal heat. When there is no perfect symmetry, the ionized sphere is disturbed initiating a non-radial oscillating pulse of electromagnetic radiation. Much of the energy is in the radiowave frequency. [Ref. 2]

For bursts occurring in the atmosphere there is greater ionization of large molecules which have a lower mobility. This lower mobility translates into an increased EMP duration. This longer pulse is expressed by:

$$\vec{E}_l(t) = 5.2 \times 10^4\left[e^{-(1.5\times 10^6 t)} - e^{-(2.6\times 10^8 t)}\right], \quad (volts/meter) \tag{1}$$

where t is time in seconds. Because of the low air density for high altitude bursts the mobility of total ions is much higher thereby the pulse is shorter and expressed by:

$$\vec{E}_l(t) = 6.3 \times 10^4\left[e^{-(1.5\times 10^{7} t)} - e^{-(2.6\times 10^8 t)}\right] \quad (volts/meter). \tag{2}$$

For lightning the rise to peak amplitude is much longer than for an EMP (see Figure 7 on page 96). By taking the fourier transform of E_l(t) and E_s :(t), the frequency signature can be derived giving:

$$|\overline{E}_l(\omega)| = \left| \int_0^{\infty} \vec{E}_l(t) e^{-(i\omega^2+\tau)} dt \right| \tag{3}$$

giving

$$|E_l(\omega)| = \frac{5.2 \times 10^4 \beta}{\sqrt{(\omega^2 + \alpha^2)}} (\omega^2 + \beta^2) \tag{4}$$

where $\frac{\beta}{\alpha} \gg 1$ $\beta = 2.6 \times 10^{8}$ $\alpha = 1.5 \times 10^{6}$. The relative decibel value equation for the long pulse is:

$$(dB)_l = 20 \log_{10} \left| \frac{\overline{E}_L(\omega)}{\overline{E}_L(0)} \right|. \tag{5}$$

Figure 8 on page 97 shows the decibel equivalents of the long and short pulse. Note that the higher altitude burst gives a higher decibel equivalent per angular frequency.

For high altitude bursts the upward traveling electrons are captured by the earth's magnetic field which then emit high frequency jamming synchrotron radiation. These electrons are called ***Argus Electrons*** and recombine slowly because of the very thin

atmosphere at this altitude. The interactions of the electrons in the geomagnetic field is shown in Figure 9 on page 98.

Due to the Lorentz force law the electrons move along the geomagnetic field lines. So the electrons spiral around the geomagnetic field lines toward the mirror point the magnetic force along the lines opposite to the motion of the approaching electrons. Thus we have electrons bouncing back and forth between the two mirror points at the magnetic poles. The period between mirrors takes approximately 0.1 to 1.0 second and the time to spiral is about one microsecond. The electrons also precess around the earth in about two to eight hours. The Argus electrons decay via recombination, reattachment, and other dissipative methods taking days or even weeks. The spiraling electrons emit a synchrotron type radiation which disrupts and jams radio communication. [Ref. 3]

The maximum frequency generated from the EMP radiation is determined by the peak time of the Compton current which is about 10 nanoseconds. Therefore the maximum frequency would be about 100 megahertz with much of the energy being in the radio frequency range. As would be expected, the peak time (rise time) is longer at lower altitudes due to the increased air density, thus the spectrum is shifted toward lower frequencies. The gamma rays only carry about 0.3% of the explosion energy and only one part per thousand to one part per 10 million of the 0.3% is radiated in the EMP. As an example, 4.2×10^{22} ergs of energy are released from a high altitude one megaton explosion. The amount radiated as EMP is about 10^{18} ergs or 10^{11} joules. It is possible that as little as one joule of energy received by a collector can damage a device.

4. EMP Pickup and Power Flow

The EMP energy is collected by a variety of conductors as seen in Table 4 on page 82. In high altitude detonations conductors outside of the source region receive very little EMP energy per unit area. The electromagnetic waves induce an electrical current in the conductors which is then carried to the connected equipment. Energy collection from an EMP depends on the size and shape of the collector, orientation of the collector, and the frequency spectrum of the pulse. Normally as the dimensions of the collector increase so does the capacity for energy absorption.

Generally solid state components are more susceptible to the EMP as compared with the old vacuum tube technology. As seen in Table 5 on page 83, the least susceptible components are motors, transformers, and circuit breakers. Regarding protection of equipment against an EMP, already existing equipment is harder to shield than new equipment with built in hardening. Grounded metal shields block

electromagnetic waves from entering the equipment while surge arrestors divert the peak current surges. Only people in contact with a collector or close to the point of detonation would be affected by the EMP radiation.

There are 3 basic modes of EMP energy coupling:

- Electric Induction
- Magnetic Induction
- Resistive Coupling (direct charge deposition).

The electric field component in the direction of the conductor creates a current. The magnetic field portion of the EMP passing through a closed conducting loop, creates a current in the loop. If a current is induced in a medium which surrounds another conductor then, an alternate conducting path is created in the conductor. Above ground collectors (e.g., antennas and power lines) are able to receive additional energy from the radiation reflected from the ground. Also underground conductors can receive EMP energy by the methods mentioned above. Because the EMP has a very broad frequency spectrum, at least part of the energy is expected to be resonantly absorbed by the energy conductors (e.g., antennas).

B. EMP ENVIRONMENTS

1. Surface Bursts

There are unique EMP characteristics associated with the height at which nuclear detonation occurs. For a surface burst, the gamma rays headed downward are absorbed by the ground thereby creating a net electron current of upward. The gamma rays not absorbed by the ground go on to produce ionization and a charge separation. This ionization results in electromagnetic waves in the radio frequency region.

Because the air at the surface is more dense than the upper altitude region, the strong electric field produced due to the charge separation decreases quite rapidly from the point of explosion. The radius for maximum EMP effects on equipment range from two to five miles. For example, a one megaton blast can create an EMP for up to eight miles.

The flow of electrons from the blast point is greater than the positive ion flow from the the blast point. Thus the core remains relatively positively charged. The electrons absorbed by the ground are conducted back to the blast point creating a strong magnetic field.

Large electromagnetic fields are generated in the ground due to the conduction current. The peak radiated fields are vastly larger along the earth's direction than for a similar air burst. The electric field being radiated a long the earth's is:

$$\vec{E} = \frac{R_{\vec{o}}}{R} \times E_{\vec{o}} \tag{6}$$

where $\vec{E}$ is the peak field at a distance R from the burst point and $E_{\vec{o}}$ is the peak radiated field at a radius $R_{\vec{o}}$. $R_{\vec{o}}$ can be about two-five miles and $E_{\vec{o}}$ can be many kilovolts per meter.

As seen in Figure 10 on page 99, the current returning back to the burst point via ground conduction produces a toroidal magnetic field. The radial component of the electric field ($E_{\vec{r}}$) and the Compton current radial component ($J_{\vec{r}}$), are related by:

$$\varepsilon_o \vec{E}_r + \sigma \vec{E}_r = -\vec{J}_r. \tag{7}$$

The solution to this equation is:

$$E_{\vec{r}}(t) = -\left(\frac{1}{\varepsilon_o}\right) \int_0^t \vec{J}_r(t')\left[e^{-\left(\frac{\sigma}{\varepsilon_c}\right)}(t - t')\right]dt'. \tag{8}$$

The fast fourier transform of the above equation gives:

$$E_{\vec{r}}(\omega) = -\vec{J}_r \frac{(\omega)}{\varepsilon^{\omega}} \left(i\omega + \frac{\sigma}{\varepsilon}\right). \tag{9}$$

By assuming high frequencies and taking the inverse fast fourier transform we arrive at:

$$E_{\vec{r}} = -\int_0^t \vec{J}(t')dt' = \frac{-Q}{\varepsilon_o}. \tag{10}$$

The surface burst has 3 phases of development. The first phase is called the ***Wave Phase*** where the displacement current is much larger than the conduction current giving the equation:

$$\nabla \times \vec{H} = \frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t} \tag{11}$$

where $\sigma \ll 10^{-5}$ *(mhmos/meter)*. The second phase is called the ***Diffusion Phase*** where the conduction current dominates over the displacement current. At this point there is electric field saturation and the toroidal current loop produces an azimuthal magnetic field as seen in Figure 10 on page 99. The third phase is called the ***Quasi-Static Phase*** where the diffusion has ceased and the induction component of the electric field is less than the electrostatic component. At this point the Compton and conduction currents start to cancel.

The ground reflection from a surface burst significantly contributes to not only the total impressed field but, also to the affects on above ground cables. The vertical component of the electric field's ground-air reflection coefficient, R_v, is:

$$|R_v| \equiv \frac{|\vec{E}^r|}{|\vec{E}^i|} = \frac{(\varepsilon - ik_o)\cos\theta - \sqrt{(\varepsilon - ik_o) - \sin^2\theta}}{(\varepsilon - ik_o)\cos\theta + \sqrt{(\varepsilon - ik_o) - \sin^2\theta}} \, (mhmos/meter) \tag{12}$$

where

$$K_o = \frac{\sigma}{\omega\varepsilon_o} \simeq \frac{18}{f_{KHz}} \quad (\textit{for a normal ground conductivity}) \tag{13}$$

σ = ground conductivity

ε_o = average dielectric constant of the atmosphere

ω = angular dielectric of the plane EMP component

ε = ground dielectric constant relative to free space

θ = angle of incidence

where

$\psi = \frac{\pi}{2}$.

The amount of energy transmitted to the ground that contributes to the current loops is given by:

$$T_v = \frac{|\vec{E}^T|}{|\vec{E}^i|} = \sqrt{1 - R_v^2}. \tag{14}$$

With the signing of a United States-Soviet Union treaty banning all middle range nuclear weapons, the use of short range nuclear weapons in combat scenarios has become more a reality. These small sophisticated nuclear weapons are capable of not only generating a significant blast overpressure, but also generating a strong electromagnetic fields within a mile or so form the point of detonation. This electromagnetic field is the source of the source region electromagnetic pulse (SREMP). There is a short and rather accurate computer program that gives information about a surface region detonation such as electric and magnetic field strength, conductivity, and Compton current given the weapon yield, range to burst, and surface conductivity. [Ref. 4]

2. Mid Altitude Burst

Medium altitude airbursts are below 19 miles with the deposition region not touching earth. Because the air closer to the surface of the earth is more dense, the electron current has a net direction upward. Weapon yield and height of burst plus weapon asymmetries determine the magnitude of the EMP field radiated. For the low frequency component of the EMP the electric field radiated is given by:

$$E(t) = \frac{R_s}{R} \times E_0(t) \sin\theta \qquad (15)$$

where R_s is the radius of the deposition region, E_0(t) is the radiated field strength at the start of radiating region of time t, and θ is the angle from the observer to a vertical position above the burst point. Common values for E_0(t) are 10-400 volt per meter and for R_s are from 3 to 9 miles.

3. Exoatmospheric Burst

For a high altitude burst(i.e., about 19 miles or greater), the gamma rays travel much farther due to the decreased air density. The gamma rays traveling upward encounter a decreasing density air while downward rays encounter an increasing density air. The source region for EMP comes from these gamma rays interacting with the air molecules. This source region or deposition region gathers about 30 miles from the earth's surface being about 50 miles thick at the center. The horizontal spread over the earth's surface is energy yield and height of burst dependent.

As the gamma rays enter the air, Compton electrons are generated. These Compton electrons are deflected by the earth's magnetic field obeying the Lorentz force law which is:

$$\vec{F} = \vec{V} \times \vec{B}. \quad (16)$$

The result is the creation of an EMP moving toward the earth's surface. The time for the EMP to rise to a peak pulse is less than the time for a surface burst because of the decreased air density. The shortened peak pulse time creates higher frequency Compton electrons used in the EMP. Thus, the electromagnetic energy for the high altitude pulse has a higher frequency. As an example, a nuclear explosion 50 miles above the earth's surface will create an affected area of 1200 miles in diameter. For a burst of 100 miles in height the affected area would be 1800 miles in diameter. Because the speed of the electrons is close to the speed of light and radiation travels at the speed of light, the entire area us affected simultaneously.

The Compton electrons in the high altitude burst will follow a curved path line around the earth emitting synchrotron radiation. The EMP radiates at angles other than vertical and from the edges. As described in Glasstone [Ref. 1], because of the conducting properties of the earth's surface, lower frequencies can extend beyond the horizon because these EM waves are able to follow the curvature of the earth. This would mean that the outer edge of an EMP would possibly have a signature more like lightning. Field strengths are on the order of tens of kilovolts per meter for the area receiving the EMP. The spatial variations in the electric field are a function of the geomagnetic field. [Ref. 3]

4. System Generated EMP

System-Generated EMP (SGEMP) refers to the electric field that is created due to the interaction of gamma and x-rays with electronic system. The gamma and x-rays induce electron forward and back scattering, via the Compton and photoelectric effects, within the system. They also create external and internal currents. In components with low gas pressure, very high electric fields can be generated at the surface. With higher gas pressures the electrons cause gas ionization and in turn release low energy secondary electrons. These electrons form a current which tend to cancel the electric field present.

The system generated EMP (SGEMP) is also known as the internal EMP (IEMP) because an EMP is generated by electric currents due to ionization from high energy photons (e.g., gamma rays and x-rays) impacting the system. Only in high altitude bursts do x-rays and gamma rays travel for enough to be of concern. For a burst welll within the atmosphere, overpressures would be a greater damage threat. The back and forward scattering of these x-rays and gamma rays interact with electronics

materials thus generating currents. Therefore spacecraft systems would feel the result of a SGEMP. However, there SGEMP effects, in some low altitude devices, called source region EMP (SREMP). The 3 modes by which SGEMP are coupled to the spacecraft electronics are:

- Replacement currents. The photons hitting the surface cause a nonhomogeneous electron surface charge density distribution. This imbalance causes induced charge replacement currents to flow on the outside of the system via electrical and electronic apertures.
- X-rays penetration of spacecraft skin. This penetration produces electrons on the interior of the walls which generate cavity electromagnetic fields. These fields produce voltages associated with spurious currents that can lead to burnout of the system.
- X-ray produced electrons injected into cables. These electrons get directly into signal and power cables again causing spurious currents that burnout the systems.

Shielding measures for cables include solid outer conductor coaxial cables. Some other means for stifling SGEMP effects include:

- back-to-back diodes for spurious voltage clipping
- decoupling networks consisting of series resistors and shunt diodes
- series inductors and shunt capacitors
- minimizing possible ground loops
- using high density packing to reduce cavity fields
- mounting components close to ground planes. [Ref. 3]

5. Electron Caused EMP

Electron caused electromagnetic pulse (ECEMP) is a result of induced transient fields, voltages, and currents in a spacecraft exposed to natural x-ray amd gamma fluxes plus a man made space environment as described above for a SGEMP. Printed circuit boards and cable dielectric act as dielectrics separating space electrons. After a sufficient buildup, dielectric breakdown occurs resulting in electrical transients entering the system. Arcing into the system occurs when floating metallization acts like a capacitor collecting charge. Other types of EMP are discussed in Appendix B.

C. EMP EFFECTS IN COMPONENTS

1. Component Selection

Voltage and current transients are system responses to the EMP and are the primary cause of damages to the system. The high altitude bursts cause much more widely spread damage than the lower altitude bursts because of the large area covered

as seen in Figure 6 on page 95. The most sensitive device to the EMP transients is the semiconductor because of their small junction areas hence small volume.

Because of the small thermal time constant of the EMP, there is an adiabatic type feature in the semiconductor. When the EMP transients approach the device failure threshold, the junctions in the devices approach its melting temperature and results in a short circuit also called ***thermal second breakdown***. This is to be distinguished from ***Avalanche Breakdown*** which occurs when the diode device is reverse biased. As it turns out, the semiconductor thermal parameters are a function of the material temperature. Some of these thermal parameters include material density, specific heat, heat capacity, and thermal conductivity.

Low-pass filters are used when hardening for EMP because of the abundant amount of high frequencies due to the brevity of the pulse. These filters come in a π or T configuration. Filters are more beneficial than shields in that they are lighter and last longer but, they must be properly used. The outside filter housing must have a good electrical grounding as determined by their design and operation.

A current limiting resistor aids in protecting them against an EMP. They basically prevent an excess current from being drawn through the base-collector junction causing breakdown and burnout. By placing this type of resistor in the emitter lead of a transistor, the device will be protected against the possibility of thermal runaway effects due to spurious currents.

2. **Cables**

The imperfections in shielded cables come from incomplete meshed outer conductor braid and from the cable connectors that are not radio frequency tight. The EMP energy induces energy on the central conductors of the cable resulting in unwanted signal currents that possibly can damage the devices to which it is connected. As described in Messenger [Ref. 3], the EMP generated electric fields can be large and the following equations give a hint to the complexity of the EMP effects on cables. The induced electromagnetic field assumed to be vertically polarized and in terms of cable parameters is:

$$\vec{E}_{zv} = \vec{E}_v^i(1 - R_v e^{-2iKh}) \tag{17}$$

where

E_v = EMP induced incident field amplitude

h = height of cable above ground

r_v = reflection coefficient for a vertically polarized wave

K = propagation number.

The internal cable voltage (V) and current (I) equations are:

$$V' = IZ = E_{zv} = Z_t I_o \tag{18}$$

$$I' + YV = -Y_t v_o = i\omega C_{12} V_o \tag{19}$$

$$Z_t = Z_d + i\omega M_{12} \tag{20}$$

$$Z_d = \frac{4(1+i)\dfrac{d}{\delta}}{\pi d^2 N N_\rho \sigma(\cos\alpha)\sinh(1+i)\dfrac{d}{\delta}} \tag{21}$$

where

- primed variables are derivatives with respect to distance along the transmission line
- I_o is total cable ground return current
- Z_t is transfer impedance between shield braid exterior and the center conductor
- Y_t is corresponding transfer admittance
- V_o is shield braid-to-ground voltage
- C_{12} is cable capacitance per unit length
- z is cable impedance per unit length
- Y is cable admittance per unit length.

Now the general form of the transfer impedance for a braid shield cable is:

$$Z_t = Z_d + i\omega M_{12} \tag{22}$$

where

$$Z_d = \frac{4(1+i)\dfrac{d}{\delta}}{\pi d^2 N N_\rho \sigma(\cos\alpha)\sinh(1+i)\dfrac{d}{\delta}} \tag{23}$$

$$M_{12} = \frac{\pi\mu_o(1-K)^{3/2}}{6N_F}\begin{bmatrix} \dfrac{e^2}{E(e)-(1-e^2)K(e)} & \alpha < \dfrac{\pi}{4} \\ \dfrac{e^2}{\sqrt{1-e^2}}[K(e)-E(e)] & \alpha \geq \dfrac{\pi}{4} \end{bmatrix}. \tag{24}$$

For electrically short ($L << \lambda$) cables, the effectiveness of the shield can be given as:

$$S = 20 \log_{10} \frac{I_o}{I} \tag{25}$$

where

I_o = outer conductor current

I = center conductor current.

When Y_t is small and terminated in impedances Z_1 and Z_2, the electrically short cable current ratio is:

$$\frac{I_o}{I} = \frac{Z_t l}{Z_i + Z_2}. \tag{26}$$

But, when Yt is large and terminated in its characteristic impedance Ze, the electrically short cable current ratio becomes:

$$\frac{I_1}{I_o} = \frac{(Z_t + Z_e Z_2 Y_t)}{(Z_1 + Z_2)} \tag{27}$$

$$\frac{I_2}{I_o} = \frac{(Z_t - Z_e Z_2 Y_t)}{(Z_1 + Z_2)}. \tag{28}$$

Now when considering electrically long cable currents:

$$\bar{I}(z, \omega) = \frac{I_o \tau}{\left[(i\omega\tau)^{1/2} + (i\omega\tau)^{3/2}\right]} \tag{29}$$

or

$$I_{(z,t)} = \frac{\sqrt{\frac{l\varepsilon_o}{\sigma} \pi\tau} \times \varepsilon_o(e^{-\frac{\tau_d}{4t}})}{L_g} \tag{30}$$

where

L_g = inductance per unit length of cable d is the cable burial depth

$$\tau_d = \mu_o \sigma d^2. \tag{31}$$

As a result, the voltage induced by an EMP with normal incidence to the cable is:

$$V = 10^{-8} A\dot{\phi}\, volts \tag{32}$$

where

ϕ = magnetic flux pulse

A = cable cross section area in centimeters. [Ref. 3]

D. EMP DAMAGE

1. Coupling

Given a shielded enclosure, the shielding effectiveness as a function of frequency is:

$$S_E(\omega) = -20 \log_{10}\left[\frac{E_i(\omega)}{E_H(\omega)}\right] \quad (db) \tag{33}$$

where

E_i = the incident electric field

E_W = electric field with the enclosure

ω = frequency.

The corresponding equation for the magnetic field is:

$$S_H(\omega) = -20 \log_{10}\left[\frac{H_i(\omega)}{H_H(\omega)}\right]. \tag{34}$$

By using Gauss's theorem it can be said that E_i must vanish in the interior of the housing for a direct current (dc) electric field. However, the dc magnetic field does penetrate the enclosure housing. A sinusoidal time dependent E_i does penetrate the housing as described by Maxwell's equations. If the shielding thickness (th) is greater than the penetration depth (skin depth, δ) then the corresponding electric field ratio is:

$$\frac{E_H(\omega)}{E_i(\omega)} = \frac{\left[\sqrt{2}\, i\omega\varepsilon_o b e^{-\frac{K}{\delta}}\right]}{\sigma\delta} \tag{35}$$

when the radius (b) and thickness (th) are measurements of a spherical shield enclosure. R is equal to the penetration distance into spherical shell wall.

As stated in Messenger [Ref. 3], the embedded medium is the most significant contribution to the overall shielding effectiveness. Also, apertures in the shield lower its effectiveness. It is noted as well that seams in the shielding can become an area for high

fields and heat losses due to a higher resistivity in these areas. For a maximum permeability μ must be at its maximum where:

$$\mu_{\max} \approx \frac{2}{\omega\sigma R^2} . \tag{36}$$

There is correspondingly maximum shielding effectiveness for shields with a high μ value. For high μ there is a quick saturation of magnetization from incident magnetic field lines after which there is no longer any protection against magnetic fields. Obviously this problem can be avoided by making the wall sufficiently thick. For time varying sinusoidal magnetic fields, the saturation penetration depth (r_s) is:

$$r_s = \sqrt{\frac{2I_{\max}}{\bar{B}_s\omega\sigma b}} \tag{37}$$

where

$\bar{B}_s$ = saturation magnetic flux density

$I_{\max}$ = peak circulating current on shield exterior.

For an incident magnetic field pulse the saturation penetration depth (r_p) is:

$$r_p = \sqrt{\int_0^{\infty} \frac{I(t)dt}{\bar{B}_x\pi\sigma b}} \tag{38}$$

where

$\int_0^{\infty} I(t)dt$ equal the total collected on the outer surface of the shield. This gives an indication of the importance that shielding thickness and shielding design can have on the protection of internal circuitry. [Ref. 3]

2. Telephone and Radio Transmission

In the event of an EMP, above ground power lines and telephone lines are particularly susceptible. Since an EMP has a broad frequency band, the sending and receiving antennas also would collect EMP energy along the designated band of frequencies. Before the concern over an EMP, power lines, telephone lines, and antennas were protected against lightning by common spark gaps. In antennas the guy wires carry most of the current to the ground via arcing. Modern spark gap devices attempt to include standards for EMP as well as for lightning. However, there are some significant differences between lightning and an EMP which merit some discussion. Just

because a device is adequately protected against lightning does not mean that it is also EMP protected.

As seen in Figure 11 on page 100, a typical EMP induced current pulse shows a rapid rise of over 10,000 amperes in less than one microsecond. The decay will last for about one millisecond. For lightning induced currents in overhead power lines, the peak current time is longer and the decay persists for a longer period of time. Therefore older lightning arresters may not be adequate. For unprotected overhead medium and low voltage power lines, surge voltages could result in insulator flashover. This can cause poor operation in the breakers in the switching surge. Radio and telephone systems employ standard measures for hardening such as buried coaxial cables, shielding of audio wiring, single point grounding, and avoidance of loops.

E. PROTECTION AGAINST EMP

1. Protective Measures

Electrical and electronic components can be rendered temporarily useless such as the temporary change of state in a flip-flop circuit. This temporary disturbance is called an ***Operational Upset***. In this situation the energy required is of a few orders of magnitude smaller than necessary to create a ***Functional Damage*** which occurs when devices or components are burned out thus permanently disallowing the full range of functions. As seen in Table 6 on page 84, *semiconductors are much more vulnerable* to EMP than vacuum tubes. Also the sensitivity of certain electrical components depend on the circuit characteristics, on the nature of the semiconductor material, and the make up of the solid state device. Obviously the sensitivity of the system and the effectiveness of the collector help in determining the seriousness of the EMP threat. But in analyzing the sensitivity of a system or component to EMP involve not only the amount of energy collected but also, operational upset and damage mechanism previously discussed. Assuming that all EMP collectors are basically similar, Table 6 on page 84 gives a breakdown of EMP susceptibility on electronics.

In determining the vulnerability of a system to EMP, the very first thing to do is to gather information concerning its components as to their worst case exposure results and susceptibility. Problem areas can then be identified, analyzed, and then finally tested.

Some general methods of hardening systems against EMP include:

- Shielding
- Proper Circuit Layout

- Satisfactory Grounding
- Protective Devices.

Also as seen in Table 6 on page 84 and Table 15 on page 90, the type of component used to design the system plays a vital role in EMP hardening (i.e., vacuum tubes versus semiconductors). Shielding involves the hindering of electromagnetic waves by highly conductive type metals (e.g., copper,iron, etc...). Individual shielding of each components proves to be very expensive and burdensome. Therefore hardening involves a continuous thick sheet or multiple thin sheets around the entire system. Care should be taken to limit the number and size of the apertures. Necessary apertures should be protected by special screens or waveguides. Also since running cables and wires can carry an induced current from EMP, they also must be protected.

Proper circuit layout would include avoiding loop layouts that would be an area for the strong magnetic field to induce a rather strong current. Other layout areas include use of common ground points, twisted cable pairs, system and intrasystem wiring. Cable design represents a mixture of shielding and circuit design measures in EMP protection. In addition, it is best to have cables deeply buried, have good junction box contacts, and have continuity of the shield layer at splices.

Without good grounding, the high peak current induced by an EMP could severely damage the system. The key is to have a relatively low impedance to the local earth surface. In addition to grounding there are other sundry ways of protecting a device. Some examples of these measures include spark gaps, arresters, low and high band pass filters, amplitude limiters, circuit breakers, and fuses. The type and particular usage of a device would determine which of these measures to be appropriate. On a smaller integrated solid state level such measures include diodes, nonlinear resistors, and silicon-controlled rectifier clamps.

In the infancy of the EMP program, specifications and standards for the hardening of systems were being explored. Hardening design had to be flexible enough to cover any present or future systems plus optimization criteria had to be drawn up for system engineering to follow involving:

- minimum initial cost
- minimum weight
- minimum Life Cycle Cost (LCC)
- minimum disruption of current operations
- maximum flexibility
- all of the above. [Ref. 5: p. 88]

In optimization of a hardening design, the bad attributes must be minimized and the good ones maximized (see Table 7 on page 84). These attributes can be categorized and quantified by use of a Figure of Merit (FOM), where FOM is equal to parameter benefits divided by parameter penalties [Ref. 6]. The major alternatives in EMP hardening include (1) shielding, (2) electrical pin protection, or (3) combination of the above. When the optimization criteria are considered, there is a fair amount of information to conclude that primary hardening should come from shielding (see Table 8 on page 85). [Ref. 5]

In most electronic devices, wire cables are used to connect the various systems. These wire cables become an obviously vulnerable source for EMP induced high amplitude voltages of short duration called transients. There is a method for protecting these wire cables from transients of any source. The Transient Protected Connector (TPC) is a device that:

- provides protection as an integral part of the envelope
- does not alter the connector envelope
- is transparent to the system
- does not significantly alter the weight. [Ref. 7]

At normal voltages the voltage variable material in the TPC, which is connected to the ground, maintains a very high resistance. When a transient hits, the voltage obviously increases and the resistance dramatically decreases as seen in Figure 12 on page 101, thus providing preferable ground pathway and protecting the system and device.

One problem that arises is whether the protective systems in place degrade over a period of time. The combination of an electromagnetic suppression filter with an electric surge arrester (ESA) system does degrade. The breakdown occurred at increasing voltage levels when measured for different years. This means that over time, the amount of voltage admitted increases on the suppression filter will increase due to a decrease performance of the ESA. As voltage increases on the suppression filter, the amount of EMP protection for the system will decrease. [Ref. 8]

2. Testing

Since atmospheric nuclear weapons testing is no longer done, other less direct methods have had to be devised to test systems for EMP hardening. Generation of an artificial EMP and computer simulations have become very common methods of evaluating the reliability of systems against an EMP. It is expected that testing systems

will reveal unexpected effects such as weaknesses or coupling. Nonlinear effects normally can be revealed by testing. The classes of EMP testing include:

- Low-level current mapping
- High-level current injection
- High-level electromagnetic fields.

Low-level current is used to indicate the magnitudes and signatures on internal cables giving the testers a starting point in system evaluation. High-level currents can help uncover nonlinearities in the system. The high-level electromagnetic field testing is the final test most closely approximating in vivo conditions.

In the tests there are two types of excitation being (1) waveform simulations providing time domain information and (2) continuous wave (CW) signals providing frequency domain information. In order to test to the electronic threshold waveform, time domain information is necessary. In matching a system to a frequency range, analysis in the frequency domain CW signals is required. The large scale simulators use the 2 types of excitation with pulse generators operating in the time domain. The pulse generator can produce a low level repetitive shot or a high level single shot. As a note, electromagnetic scale modeling appears to be useful to the measurement of external fields, voltages, and currents. Internal field quantities are harder to come by. Some important simulators are discussed in Appendix C.

One method of simulating EMP employs a large parallel plate system generating a maximum amplitude of 100 kilovolt per meter with a rise time of 10 nanoseconds. In this arrangement small and medium size objects can be completely irradiated at realistic amplitudes. [Ref. 9]

Also, in experiments the use of fiber optics in measuring shield effectiveness for a high altitude EMP, have improved the accuracy of such measurements. By mounting the magnetic field sensor on a fiber optic cylinder, the amplitude of the EMP was enhanced. Some of the advantages of the fiber optic cylinder include:

- elimination of signal cable coupling
- protection of electronic devices used in field data collection. [Ref. 10]

However vibration, corrosion, aging, improper maintenance, and modifications can cause the shielding effectiveness to be compromised. The Defense Nuclear Agency (DNA) continuous wave (CW) Measurement System is used to test the electromagnetic response of systems. The 3 functions in shielding performance are:

- excitation of the system
- observation of the system response
- interpretation of the observed response. [Ref. 11]

The CW system is portable, repeatable, automated, and gives real time data processing. Flexibility in tailoring testing to specific system requirements and flexibility in providing the type of electromagnetic excitation of potential gradients makes it a powerful tool for shield testing.

III. HAZARDS OF ELECTROMAGNETIC RADIATION TO ORDNANCE (HERO)

A. INTRODUCTION

The HERO program's existence and continuation is established by OPNAVINST 8023.2c dated 19 June 1981. Within this program, the Navy Explosive Safety Program receives policy, requirements, and procedures. The HERO programs official Navy point-of-contact is the Naval Sea Systems Command. They act as the principal coordinator between the HERO Program and the Naval System Commanders plus they must resolve all electromagnetic radiation hazards affecting ordnance. The instruction governing the Naval Sea System Commands role is in NAVSEAINST 8020.7B dated 25 August 1987. Other instructions providing technical guidance for the HERO program are MIL-STD-1385B dated 1 August 1986, NAVSEA OD 3095 dated 1 September 1974, and NAVSEA OP 3565 dated 1 May 1987. [Ref. 12 and 13]

In paragraph 4 of NAVSEAINST 8020.7B the scope of the HERO program is quoted as follows:

a. The HERO program shall establish and implement HERO explosives safety standards, criteria, instructions, regulations,and electromagnetic emission (EMCON) regulations throughout the Department of the Navy in accordance with the organization and general responsibilities assigned by reference (a).

b. This instruction applies to programs involving weapon systems for surface ships, submarines, aircraft, and installations.

c. The HERO program includes nuclear and conventional electrically initiated weapons such as: gun systems, missile systems, bombs, flares, powered targets, depth charges, mines, torpedoes, and other items that contain EED's (e.g., cable cutters, chaff, and munitions dispensers, self destruct devices , fire extinguishers, etc....). In application, this instruction applies to operations and equipment utilized in assembling, packaging, processing, stowage, handling, and testing plus the disposal of weapons and launching systems which contain EED's.

d. This instruction is also applicable to EMR emitters being developed or modified for use in areas adjacent to the deployed Navy Weapon Systems.

e. This instruction implements and is part of the Weapons System Safety and Explosives Safety Programs. [Ref. 14]

In addition to the definition outlined above, some of the responsibilities included in the HERO program are as follows:

- Proposes changes to future weapons development to ensure safety from electromagnetic radiation (EMR)
- Maintains procedures for HERO certification
- Tests for HERO certification on platforms (e.g., ships, etc....)
- Certifies whether a particular weapon is safe or not in a particular platform environment
- Maintains files of HERO certification of all Navy Weapon Systems.
- Inspects transmitting and receiving antenna installations to avoid any possible HERO problem
- *Maintains* NAVSEA OP-3565. [Ref. 15: p. 1-5]

Within the HERO program ordnance is labeled safe, unsafe, or susceptible and under what conditions is that ordnance safe, unsafe, or susceptible. This means any restrictions necessary to make that ordnance safe must be spelled out clearly. These restrictions may involve special movement and handling procedures detailing the limited operation of EMR generating devices within the local area. These restrictions may be incorporated in the HERO EMCON bills of restrictions for ship and shore commands.

HERO testing, EMV testing, the missile E^3 program, and the Electronic System Effects program are all supported by the NSWC, Dahlgren, Virginia. Some of the facilities include a ground plane, mode-stirred chamber, anechoic chamber, and the transmitters. The EMV program started in the early 1970's.

1. Pre-HERO Program/History

As early as the 15th century specific hazards were associated with artillery and precautionary measures were taken. It has only been since the early 1960's that there has been a standard accident format to report unexplained accidents that could have been caused by RF emissions. A brief history of Hero and EEDs is seen in Appendix D.

In the late 1800's, Michael Faraday and Heinrich Hertz demonstrated that EMR can induce a current in conducting wires. Also in the second half of the 19th century a British citizen, Alfred Nobel, patented the electric blasting cap It has been RF and EED technologies that have created the HERO program. The connection between these two technologies was not suspected until World War II. It was recognized that certain accidents and machinery reliability problems were being caused by an induced current in the wires leading to that ordnance's EEDs. The unshielded conductors, personnel, and tools were acting as an antenna conveying the induced current.

Modern ships are no longer made of wood (except Mine Sweepers) but of metal which has a good ground in the ocean. Since the introduction of radios and then later radar, the ships have been an increasing source of EMR and expectantly produces an interference problem. There is mutual interference between communication equipment as well as between radars and electronic wave equipment as well as between individual radars. In recent years, the radiation power levels of the radar, particularly in the form of phased-array radar (e.g., AN SPY-1), have increased and will continue to complicate the EME picture even more. As will be discussed later these increases in the radiated power levels will cause retesting and re-certifying of the EEDs and weapon systems respectively. The HERO program's task of investigation of potential HERO problems, prevention of EMI problems, and suggested controls on electromagnetic emissions becomes increasingly important as technology provides more equipment for shipboard use.

As part of the testing of EEDs, a device had to be found that could convert the heat of the bridgewire to a measurable electric current. After a contract period from 15 March 1956 to 30 November 1960, by what is now the Naval Surface Warfare Center (NSWC) with the Denver Research Institute (DRI), the thermocouple proved to be the most promising sensor.

2. Regulation Guidance

In order to avoid HERO problems in new weapon systems and ordnance in 1961, the HERO program was directed to provide guidance to manufactures of weapons in the early stages of development in order to ***design out*** HERO accentuating conditions. There were two objectives in mind:

- provide timely HERO information to weapons developers
- provide an environment whereby weapons developers can bring problems to the HERO program staff.

The problem solving team consisted of HERO experts from:

- NAVAL WEAPONS LABORATORY (NWL)
- NAVAL ORDNANCE LABORATORY WHITE OAK (NOL WO)
- NAVAL DEVELOPMENT CENTER JOHNSVILLE (NADC J)
- NAVAL ORDNANCE TEST STATION (NOTS)
- NAVAL ORDNANCE LABORATORY CORONA (NOL C).

The background of this problem solving team were areas such as proximity pulsed radar technology, physics, electrical engineering, cameras, transmitters, and radio receivers.

3. Methodology

If current operation procedures aboard a vessel do not meet HERO standards regarding use of weapon systems, RF radiating equipment, or handling of ordnance, then either an administrative fix or a physical fix would be needed. A physical fix would consist of using hardening technology such as shields and filters in order to reduce the amount of hazardous RF induced current. An administrative fix might consist of the following type of measures:

- controlling RF emissions during critical ordnance handling operations
- stipulation of ***safe handling distances***
- modification of a critical ordnance handling operation. [Ref. 15]

Appendix E clearly shows the trends toward an increased number of frequencies and increase power density in the communications and radar type equipment. [Ref. 16]

As a result of the increased frequency range and greater power density there was a need to reevaluate the HERO status of previously tested weapons systems. What the HERO program testing personnel did was to extrapolate from valid data by multiplying the known 15% MNFC by a scaling factor. This scaling factor was the ratio of current power density to power density at test time. As might be expected there was considerable engineering judgment and worst case scenarios were always considered when determining a safe level. By increasing the field intensity of the 2-32 MHz HF band from 100 V/M to 200 V/M, the testing personnel had to also reevaluate the ordnance handling and loading procedures. There are two possible solutions to this problem:

- retest and reclassify all systems at the 200 V/M field strength
- modify the general HERO requirements of ordnance separation distance from an HF antenna. [Ref. 15]

4. Design and Inspections

Some possible solutions to the HERO problem are:

- eliminate all EEDs
- physical separation of all EED ordnance from an EME
- remove or turn off all EME generating equipment when EED ordnance is presented
- harden all EEDs and components in ordnance. [Ref. 17]

The most popular solution by the fleet is hardening and appears to be the most feasible long range answer. As discussed in the ***hardening*** chapter the proper use of filters, shielding, and circuit layout can adequately protect a system.

Since 1962 designs and standards for the RF environment were determined and put into instructions and reports to be used by ship and shore communities. Table 9 on page 85 and Table 10 on page 86 show the initial environmental conditions to be used by ship and shore activities in protecting ordnance. It was not until 1964 that RF environmental criteria information became a military specification carrying more authority than the previous articles, but yet containing the same environmental information. This new specification dictated that a weapon enclosure shall attenuate RF energy at least 60 db from 1 MHz to 20 MHz [Ref. 18]. Along with this information ***susceptibility curves*** can be generated as seen in Figure 13 on page 102 and in Figure 14 on page 103. They provide information for field strength and power density for all interested parties (e.g., weapons officer, and weapons designers). By 1965 the first edition of reference 29 was produced in order to fully incorporate design guidelines and principles for weapons designers and testers in order to meet HERO standards and requirements.

As communication equipment and radar began to require greater power and frequency usage, the HERO program had to reject this trend in their testing and standards. A new military instruction reflected this change when MIL-STD-1385 replaced MIL-D-24014 on 6 April 1972 [Ref. 16]. Appendix E gives a table for the 1972 EME levels. Not too many years after this new instruction, the upgrade of reference 29 was released also giving updated **susceptibility curves**. These curves give information for single component level EED and also hazard levels for fully assembled weapons during loading and handling. These new updated graphs are shown in Appendix G.

B. THERMOCOUPLE

The Denver Research Institute (DRI) was contracted to develop a sensor which could measure the heat generated in the bridgewire of the EED from RF energy induced currents. Bismuth and Tellurium were the most sensitive thermocouple materials. But, Tellurium was too hard to deposit on thin films and a Bismuth-Tellurium mixture had problems such as high impedance, fast aging, and electronic drift. All of these made it very difficult to properly calibrate the Bi-Te mixture. The final selection was a Bismuth-Antimony combination which does not have the same problems as the Bi-Te thermocouple also the Bi-Sb has a sufficient sensitivity. Table 11 on page 87 gives a brief summary of DRI's work in this area.

Where these thermocouples are used determine, to some extent, the thermocouple's desirable qualities. In field testing these sensors are used to indicate the joule heating

in bridgewire of EEDs in a particular missile or rocket on a particular platform so as to determine the actual degree of hazard to ordnance. In laboratory testing thermocouples are used to indicate joule heating in bridgewire of EEDs in order to study the method of RF power transfer. The requirements for field testing sensors are:

- be sensitive enough to detect bridgewire temperature rises which are small compared to the ambient temperature
- be compatible with miniature portable equipment
- are expendable and required in large quantities leading to lowest and easy fabrication.

Also, the requirements for laboratory testing sensors are:

- should be capable of detecting very small amounts of power dissipated in the bridgewire in order to determine RF coupling
- could involve large and complex equipment
- are not expendable and required in small quantities.

As noted in Table 11 on page 87, vacuum deposited thermocouples are lower ranked than others, but are the most practical sensors overall. Also toroidal coil, PEM, and wire thermocouples do not significantly hinder its performance. Only small variations in thermocouple resistance and output are caused by humidity and after 100 days 90% of the thermocouples had changed less than two ohms. These results are for thermocouples that contain silver ink connections. Thermocouples are made according to the following process:

- fabricate a mechanical mold
- pour base materials into one mold and allow to harden
- machine this hardened base and apply a Mylar substrate
- apply layers of Bi-Sb
- apply RF shielding
- calibrate assembly (i.e., thermocouple plus inert EED).

The Bi-Sb vacuum deposited thermocouple invented in the early 1960;s continues to be the EED of choice. More powerful and efficient vacuum pumps that have aided to create a better environment to deposit a metallic thin film, have increased the capacity of production. Other techniques, (e.g., the use of Mylar to reduce the thickness and reduced the width by a factor of 10) have greatly improved the response time and

sensitivity of the thermocouples. Currently the specifications of the thermocouples produced at NSWC, Dahlgren are:

Sensitivity	90-100 V/^{o}C
Response Time	20-35 ms
Resistance	4-20 Ω.

By experimentation the group at NSWC, Dahlgren discovered that if a thermocouple is aligned at 45° in a plane normal to the EED bridgewire, there is a maximum response time and sensitive [Ref. 15]. This same group noted that in situations where a thermocouple could not be placed, the use of temperature sensitive chemical substances (e.g., beeswax) could be used to sense the bridgewire heat. The temperature range could be from 100°F up to as much as 3200° F with a 3-7°F sensitivity. [Ref. 15]

C. GROUND PLANE TRANSMITTER

The ground plane serves as the shore testing area located as NSWC, Dahlgren, VA. It measures 400 feet by 100 feet covered by 1 4 inch weld steel plates. Connected long copper rods were drawn into the ground to accurately measure the ground potential. Transmitters were needed to generate the RF environment and the first ones used in 1961 are described in Table 11 on page 87. In the space of less than one year, band specific transmitters were allowed to be used, in addition to the ground plane transmitters, as also seen in Table 11 on page 87. [Ref. 15]

As seen in Table 13 on page 89, the ground plane provided an increased capability of frequency and power output over the years. Also some of these transmitters are portable in order to provide dockside testing of ships [Ref. 15]. Table 14 on page 89 shows the improvement in the type and quality of the ground plane transmitters since 1972.

The Bruceton sensitivity test is used at a particular frequency by the HERO group in testing EEDs for mean, all fire and no fire stimuli levels. These levels are defined as follows:

- **Mean-Stimulus Level-** the level that will produce a function response 50% of the time
- **All-Fire Stimulus Level-** the lowest level that will consistently produce a function response
- **No-Fire Stimulus Level-** the highest level that will consistently fail to produce a function response. [Ref. 19]

Some of the stimuli associated with EEDs are (1) constant current; (2) constant voltages; and (3) capacitor discharge energies. In this type of test the estimated mean and standard deviation are both used to derive more accurate ones. The more accurate μ and σ are then used to determine the all-fire, mean and no fire levels. This method is very similar to the one-shot method.

Before the test takes place, the distribution of stimulus levels are logarithmically spaced to ensure a gaussian distribution. However, an estimated μ and σ are used to set up the range of levels to run the test with the step size increase equaling to σ. After the test a new μ and σ are produced.

If a mean firing level is known, it should be used to determine a preliminary σ. If it is not available, a single device should be stimulated at a no fire stimulus level and increased until the device fires. Numerous trials on one device should be avoided in order not to obscure results through repeated use of the same device because of desensitization. This method assumes that the voltage and current levels are constant and have a running length from milliseconds to seconds while capacitor discharging should last about one second. According to reference 39, the estimated σ should be from 0.01 to 0.025 logarithmic units for the capacitor discharge, constant current, and constant voltage tests. As stated before, the σ becomes the step increase for the test. The preliminary Bruceton test run uses 20 devices and should occur at room temperature. The 20 devices and should be a random sample (i.e., preferably not all of them should come from the same lot). Starting at the mean firing stimulus, the first device should be tested and each time a device does not function the firing stimulus level should be raised by σ for the next device and vice versa each time a device does function. Upon completion the test should not have covered less than two levels by not more than six otherwise adjustments must be made. From this preliminary run a new μ and σ can be determined and another 50-100 runs can be made with the new values. The σ can then be adjusted to ensure that 10% of the runs occur equally at the extremes. From this main Bruceton test another set of μ and σ can be determined which determine the all fire and no fire levels for the devices which are 99.9% and 0.1% respectively. By using 100 devices in the main test a 95% confidence level is assured. The % firing level equations are:

99.9% Firing Level $= \bar{x}$ (mean) $+ 3.09\sigma$

00.1% Firing Level $= \bar{x}$ (mean) $- 3.09\sigma$.

[0]Ref. 19

The ground plane was built to simulate shipboard EME. It consisted of steel plates and built over an airplane parking area. Test transmitters were mobile vans with shipboard antennas. It provides a flexible, cost savings, and more accurate testing method than does fielding testing. Field testing of ordnance for HERO created interruptions of shipboard operations along with man power. Also the testing power levels for HERO were hazardous to shipboard transmitters. Therefore the ground facility at NSWC, Dahlgren has proven to be more effective than field testing. [Ref. 15]

D. ELECTROMAGNETIC ENVIRONMENT (EME)

1. Power Levels

The power in the EME is a factor of:

- power radiated from the source
- distance of ordnance from the source
- source antenna gain.

For the time being the radiation source is considered isotropic in free space, therefore the power density (P_A) is proportional to the average power in watts (W_A) and inversely proportional to the surface giving:

$$P_A = W_T/4\pi r^2. \tag{39}$$

If the source is not isotropic but exhibits a specific directional gain, the right side of the above equation would be multiplied by the source (or transmitting) antenna gain G_T. For a far field the power density equals the square of the electric field strength divided by the intrinsic impedance 120π or:

$$E = 19.4\sqrt{P_A} \tag{40}$$

where the electric field is measured in volts per meter and
P sub A = left .lbrack < W over m sup 2 > right .rbrack .
Combining the P_A equation in the far field equation results in:

$$P_A = \frac{G_T W_T}{4\pi r^2} \tag{41}$$

showing a prefered direction of gain. Now if $G_T = 1.64$ (for a dipole) then:

$$E = \frac{7.01}{r}\sqrt{W_T}. \tag{42}$$

By redefining gain in terms of decibels (dB):

$$g_T = 10 \log G_T \quad (dB) \tag{43}$$

or

$$G_T = 10^{\frac{g_T}{10}} \tag{44}$$

The susceptibility curves seen in Appendix G have had to take into account pulse modulated radar as opposed to a CW or doppler system. In this pulse modulated environment the ratio between the average power (W_A) and the peak power (P_P) is an important parameter called the ***Duty Ratio*** (DR) where

$$DR = \frac{W_A}{P_P} \tag{45}$$

also

$$DR = pulse\ width\ x\ pulse\ rate = \tau fr. \tag{46}$$

Given the peak power and duty ratio the W_A can be determined where:

$$W_A = P_P x DR = P_P \tau fr = \frac{P_P \tau}{T} \tag{47}$$

and

$$T = \frac{1}{fr} = pulse\ repetition\ time. \tag{48}$$

These relationships are graphically illustrated in Figure 15 on page 104.

2. Antennas

When discussing shipboard antennas there are two basic types:

- large radiators
- small radiators.

Large radiators are characterized by a large antenna length to transmitted frequency ratio (i.e., greater than one) whereas small radiators have a ratio less than one. The half-wave dipole antenna is an example of a small radiator as seen in Figure 16 on page 104. Most of the large radiators have a dish and is represented in Figure 17 on page

105. Note the much higher gain over isotropic for the reflector antenna. The reflector design allows for the alteration of the phase and amplitude in order to focus the radiation. Measurements of the field strength aboard a particular platform (e.g., an aircraft carrier) can only be measured for ***Fraunhofer*** or far field regions. A Fraunhofer region or Fraunhofer diffraction occurs when the wave from a source (e.g., an antenna) appears as a parallel wave [Ref. 20]. Figure 18 on page 105 shows the typical field strength contour of a carrier deck and illustrate how difficult and irregular the measurements can be. The near field or ***Fresnel*** region obviously start at the source up until the start of the far field or Fraunhofer region. Because of the relatively short near field distance, it does not come into play regarding HERO issues unless the ordnance is right upon the radiating source.

3. Electromagnetic Energy Transfer

The amount of energy received by an object depends on the amount of area available for reception times the power density in the location of the receiver. Now the available or effective area is given by:

$$A_{eff} = \frac{G_R \lambda^2}{4} \pi \tag{49}$$

where

λ = wave length in meters = 300 frequency in MHz

G_R = gain of receiving antenna.

Recalling the equation for P_A gives us an equation for watts received (W_R):

$$W_R = \frac{G_R G_T W_T \lambda^2}{4\pi r^2} \tag{50}$$

or

$$W_R = \frac{G_R G_T \lambda^2 P_A}{4\pi} . \tag{51}$$

These equations assume an impedance and load matching as well as a maximum effective area available. In order to determine the current in say a bridgewire, just relate the watts received to the current by:

$$W_R = I^2 R. \tag{52}$$

These equations give a worst case scenario and assume:

- no shielding of radiation
- no filtering of radiation
- no losses due to load impedance mismatches
- no losses due to resistance in transmission lines or atmosphere.

As seen in Figure 19 on page 106 there are several ways in which an ordnance could function as a receiving antenna. Also platforms such as aircraft and ships have even more ways as acting as receiving antennas which includes human personnel.

In summary, the HERO program is a specialized area of electromagnetic vulnerability involving the EED within ordnance. Being that EEDs are in many types of mechanical systems, the HERO programs can be generalized to cover any mechanical systems involving EEDs. Electromagnetic fields of known power, frequency, and duty factor for various types of radar and time domains (i.e., from CW to pulsed excitation) are the generating sources for the HERO effect as discussed in sections A and B. Section C shows how these sources are artificially induced to quantify and analyze thus setting safety and reliability standards. In discussing the actual operational environment section D gives a clear picture of the transfer mechanisms and its variables from source to the energy and current induced within the EED containing device.

IV. HARDENING

A. HARDENING TECHNIQUES

1. Shielding

In some cases knowing the maximum level of shielding protection that a metal can provide would be useful. Kunkel [Ref. 21] has developed an equation to calculate the shielding effectiveness (SE) that can be used on a hand held calculator. This equation could not be used for evaluating an actual shield because some of its assumptions are that (1) the barrier is infinite in size, (2) the barrier is flat, and (3) the barrier is homogenous:

$$SE = R + A + B(db) \tag{53}$$

where

$$R = 20\,\frac{\log(k+1)^2}{4|k|} \quad \textit{reflection loss (db)} \tag{54}$$

$$A = 8.686 \quad ad \qquad \textit{absorption loss (db)} \tag{55}$$

$$B = 20\log\left|1 - \frac{[k-1]^2}{[k+1]}\,e^{-2(1+j)}ad\right| \quad \textit{reflection correction (db)} \tag{56}$$

$$K = \frac{Z_{wave}}{Z_{barrier}} \quad , \quad Z_{barrier} = \frac{[j\omega\mu]^{1/2}}{[\sigma]} = \frac{1+j}{\sigma\delta} \tag{57}$$

$$Z_{wave} \simeq -j3772\pi r, \quad (r < \frac{\lambda}{2\pi}) \quad \textit{high impedance source} \tag{58}$$

$$Z_{wave} \simeq +j3772\pi r, \quad (r < \frac{\lambda}{2\pi}) \quad \textit{low impedance source} \tag{59}$$

$$Z_{wave} \simeq 377, \quad (r \geq \frac{\lambda}{2\pi}) \quad \textit{sources} \tag{60}$$

$$a = \left[\frac{\mu\sigma\omega}{2}\right]^{1/2} = \frac{1}{\delta} \tag{61}$$

also

d = thickness of barrier (meters)

r = distance from source to barrier (meters)

$$\omega = 2\pi f \tag{62}$$

μ = (absolute) permeability of barrier

σ = (absolute) conductivity of barrier

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{f}. \tag{63}$$

Most shielding rooms are made of heavy-gauge magnetic steels. The American Society of Testing Materials (ASTM) is drawing up standards for the testing of lighter weight materials as of 1984. There are many techniques for measuring the shielding effectiveness of enclosures. Some of these techniques of shielding effectiveness are investigated and the advantages and disadvantages are spelled out. Some of the methods involve the use of adjoining transverse Electromagnetic (TEM) cells and a time domain receiver system [Ref. 22]. In conclusion, shielding can be outlined as follows:

- For magnetic fields, only magnetic material can be used for shields at low frequencies
- For electric fields, materials with high σ are adequate for shields
- For plane waves, materials with high σ are adequate for shields (both magnetic and electric fields)
- For any given material, a greater shield thickness is required for magnetic fields than for electric fields
- For any given material, a greater shield thickness is required for low frequencies than for high frequencies
- For high frequencies absorption losses become important therefore, to maintain the shielding effectiveness, all openings must be closed. [Ref. 17: p. 41]

2. Cables

Copper and nickel are the materials aptly suited to shield cables. A single braided cable gives 50 to 80 decibels (db) of protection over the EMP spectrum whereas the double braided gives 70 to 100 db and the solid conduit provides more than 110 db of protection.

The ***EMP response*** is being used to specify shielded cable and is a figure of merit (FOM). This FOM combines the frequency content of an EMP with the frequency dependence of the transfer impedance of the cable shield and then integrate over the

frequency domain. The EMP response FOM specificaton is 60 db. Given this specification cable designers should design cable shields with less than one milliohm per meter of resistance and less than 200 picohenries per meter of inductance. [Ref. 23]

3. Apertures

Apertures in a shield of nearly any size can be penetrated by electromagnetic waves induced in an EMP. One example of this phenomena exist in braided coaxial cable. The length of the cable determines the induced current levels. Mathematical formulas are used to calculate the load currents of fixed length coaxial cables. [Ref. 24]

Hardening techniques for points of entry are shown in figures Figure 20 on page 107 and Figure 21 on page 108.

4. Circuit Design

Circuit hardening techniques are shown in Figure 22 on page 109 and Figure 23 on page 109.

5. Antennas and Filters

Figure 24 on page 110 and Figure 25 on page 110 show techniques for protecting antennas from the EMP signal.

B. HARDENING DESIGN

1. Allocation

It is unrealistic to expect complete protection of military ships and aircraft from any type of EMP or HERO. Two questions arise when discussing protection against EMP:

- What amount of protection needed?
- How do you allocate protection to various systems?

The fundamental approaches in protecting a system or circuit from outside sources are:

- eliminate the source
- eliminate the circuit
- separate the source from the circuit
- electromagnetically shield either the source or the circuit. [Ref. 25]

Obviously shielding the circuit is the most feasible option. Electromagnetic waves can enter the circuit area via aperture and penetrating conductors (i.e., wires leading to and from the circuit) despite the presence of a metal shield being present. It is also obvious that this outer shield be the outer shell of the aircraft or ship, but this is insufficient protection from EMP as noted in Figure 26 on page 111. Another level of shielding

covering specific EM sensitive systems circuits. Protection is sufficient when external EMP stresses are no longer the dominant stress. When system generated stress is more significant than the external EMP, system protection from the external EMP can be classified as sufficient. These internal stresses are created by power switching, rectification, relay coils, solenoids, etc... (see Figure 26 on page 111).

2. Margins

One equation to designate EMP hardness margins (EHM) is:

$$EHM = 20 \log_{10}\left(\frac{I_{damage}}{I_{spec}}\right)(db) \tag{64}$$

where

I_{damage} = current needed to damage a device

I_{spec} = maximum current level at the device interface.

A margin of 10 decibels is considered satisfactory.

3. Component Selection

The surface currents generated by an EMP can be up to 30,000 amps of many microseconds duration. There are two types of disturbances that an EMP can cause (1) transient upset, and (2) burnout. Both of these are due to spurious currents. Transient upset requires less current than burnout and can trigger flip-flops which cause high speed computer malfunction. Permanent damage is caused by burnout which is seen as overheating and voltage breakdown which leads to arcing carbuerization.

In order to effectively harden components, it is necessary to give them low pass filter characteristics in order to shunt the bulk high frequency portion of the pulse. Some guidelines given to consider include:

- Bipolar devices with a large threshold failure per unit area (Wunsch-Bell constant) should be used
- Long switching times should be used for maximum rise times and storage times
- Components should have a high junction capacitance
- Use additional input and output shunts and integrating capacitance in order to slow circuit response.

The most susceptible devices to EMP are microwave diodes, transistors, and integrated circuits. Table 15 on page 90 gives the relationship between type of device and failure energy for some common devices.

In semiconductors studies discussed in reference (2), it has been discovered that diode or transistor junction devices can withstand a very large, short duration power pulse surge. This is in contrast to its continuous service rating. Also the shorter the EMP pulse duration, the greater the peak power that is able to be withstood. These studies assume a rectangular pulse using the Wuncsh-Bell model given by:

$$\frac{P_f}{A} = Kt_f^{-1/2} \tag{65}$$

where

P_f = failure power threshold of the device (kW)

A = junction power threshold of the device cm^2

t_f = duration of rectangular EMP (microseconds)

K = damage constant $kW(\mu s)^{1/2}/cm^2$.

Table 16 on page 90 provides some guidelines for picking a damage constant.

The design of ship and aircraft systems is beginning to include the EMP problem. The design procedure includes a computer-aided interactive process involving computational and experimental techniques. The EMP algorithm parallels the Electromagnetic Compatibility design approach in exterior radio frequency communication system design. Hazardous Electromagnetic Radiation Effects on Ordnance (HERO) and EMP have a common relationship in that both require hardness design (e.g., filters and shielding) but the type of filters and shielding is quite different. [Ref. 24]

4. Methods

When selecting components to build a particular device there are some circuit hardness measures to consider. Components are chosen for:

- a minimum ionizing radiation response via low circuit impedance
- fast recovery times
- a minimum permanent damage.

Some sorts of time delay methods (e.g., relays, magnetic cores, and certain radiation insensitive tunnel diodes) can be useful in circuit hardening.

Some of the most common system hardening methods are:

- Reset
- Redundancy
- Circumvention

* Hardening of computer memories
* Hardening of microprocessors and computers.

Reset involves being able to restart an electronic device or system after it has malfunctioned possibly due to and EMP. Redundancy is simply to supply backup systems in case the main systems are brought down by radiation. One problem with this method is cost and therefore allocation of redundancy in electronic systems. Should you duplicate units within a system or the entire system? Figure 27 on page 111 shows that unit duplicity gives a higher reliability. Circumvention is an electronic process whereby the system goes into a standby mode when the incident nuclear pulse amplitude goes above the logic upset level. As seen in Figure 28 on page 112. the radiation detector must cause the inhibit logic to freeze the computer memory store before the pulse amplitude causes upset or damage. In particular, the incident radiation can cause memory modification of any memory word being accessed by the central processing unit at the time of radiation impact upon the system. Protection of computer memories and microprocessors is accomplished by selecting radiation resistant semiconductor devices such as bipolar logic devices and a combination of the above methods.

For shielding effectiveness testing, typically a two-port drive circuit technique is used. This method involves a signal generator applying a signal at one side of the shield and a detector measures the amount of signal leaking across the shield. This would also apply to radiated fields. The two-port method has some problems which can affect the reliability of the measure of shield effectiveness by:

* Most two-port measurements do not completely characterize the shield
* Voltage at one end of the sense line is not equal to the voltage at the other end
* Results of the two-port method do not scale linearly with length.

The four-port drive circuit technique takes into account that the voltage at one end of the sense circuit is not the same at the other end. Also with the drive signal being applied at one end of the cable shield, the far end terminates with some load. If as seen in Figure 29 on page 112, the impedances at each end of the drive and sense circuit are not the same, then errors will result. [Ref. 26: p. 85] The advantages of the four-port method include:

* far end and near end leakage can be measured
* shield leakage results scale linearly with length
* allows shield leakage measurements to be compensated for any set of impedances on the drive and sense lines. [Ref. 26: p. 84]

In the HERO program hardening of ordnance and weapons systems is complicated by having to deal with (1) ordnance currently deployed in the fleet but. improperly protected; (2) the need for increased flexibility in fleet operations; and (3) ordnance designers and manufactures attempting to deliver weapon systems and ordnance quickly and at a low cost to themselves. In hardening an ordnance already deployed involves part science and part creative art in order to protect it yet keeping its effectiveness. Figure 30 on page 113 shows some proper and improper methods for hardening and Table 17 on page 91 gives information on shielding materials.

5. Grounding

For ground based facilities an effective method for reducing the level of an EMP current entering the facility is to provide additional paths to drain the energy before it enters the building via grounded external collectors. It is the long external power lines providing the major threat to sensitive equipment inside. One solution is to locate the power line ground entrance away from the building plus shielding and grounding the transformer. Some conclusions from research are:

- For power line lengths up to 50 meters, there is a direct relationship between line length and induced current and beyond 50 meters less of an effect
- Multiple grounds give only a secondary effect of EMP pickup by overhead power lines
- Remote location of the power transformer from the building is appropriate. [Ref. 27]

Figure 31 on page 114 gives a summary of grounding techniques.

V. ELECTROEXPLOSIVE DEVICE (EED)

A. DEVELOPMENT

Electrical detonation of black powder was accomplished in 1745 by Doctor Watson of England. Benjamin Franklin invented electric initiation in 1750 whereas Doctor Robert Hare developed the bridgewire electric blasting cap in the early 1800's. Also a fine platinum bridgewire blasting cap was created by H. Julius Smith. With the bridgewire there could be testing of the cap circuit. These first bridgewires were 90% platinum, 10% iridium, 3/16 inch long, two mm in diameter, and have a 60 ohms resistance. Some other uses for EEDs are:

- rocket motor ignitors
- electric switches
- mechanical movement in fuses and valves
- thermal batteries
- cable cutters.

There are now more than 100 commercial manufactures of EEDs for commercial and military uses.

B. DEVICES

Electroexplosive devices are defined as initiator type components which use ac or dc electrical current energy to act off an explosive propellant or pyrotechnic material [Ref. 17]. Since EMR energy can induce a current in a conductor, as described by Faraday and Hertz in the 19th century, the EME and its control becomes paramount. This is the heart of the HERO problem and the use of EEDs is the HERO problem. Table 18 on page 92 shows some typical applications for EEDs.

There are four possible hazards involving EEDs which are:

- **Inadvertent Initiation** which is out of order firing resulting in premature firing or reduced effectiveness
- **Dudding of EED** which happens as a result of insensitivity of EED over a period of time resulting in a reduced reliability
- **Thermal Stacking** which occurs as a result of pulsed radar heating the bridgewire below the firing temperature as seen in Figure 32 on page 115

Now there are three modes of RF excitation in an EED which are:

- Differential RF mode as seen in Figure 33 on page 115 where balanced wire leads propagate EM energy to EED
- Coaxial firing system between two concentric conductors, as seen in Figure 34 on page 116
- Coaxial mode on a two wire balanced shielded system as seen in Figure 35 on page 117 where the shield is the outer conductor and the wire leads the inner conductor. [Ref. 17]

EEDs can be categorized in four groups which are:

- Hot Bridgewire Devices (HBW)
- Exploding Bridgewire Devices (EBW)
- Conductive Mix EEDS (CME)
- Carbon Bridge EEDs (CBE).

Currently conductive mix EEDs are not used by the Navy because design problems and ease of induced RF currents. Because the voltage sensitivity of the carbon bridge EED and its sensitivity to induced EM energy, they are not used as well. The Hot Bridgewire devices are the most commonly used. The EBW device has the advantage of requiring a high current for a short period of time in order to initiate but can be burnt out with an insufficient current. [Ref. 17]

C. CHARACTERISTICS

1. Parts

The EED is composed of three parts which are:

- inert support structure, the shell or casing
- electro-thermal transducer, the bridgewire
- explosive, detonation material or initiator material.

The main focus is to convert wire current (i.e., electrical energy) to thermal energy or a shock wave as a result of heat expansion. As seen in Figure 36 on page 117, if there is a sufficient temperature increase of the electrothermal transducer for a modest time span, there is a ***zone of regenerative reaction***. On the other hand, regions A and B represent the extremes regarding time and temperature as an inverse reciprocal of each other. The ***transition zone*** can be represented in terms of probability of occurrence.

The EBW transducer works by the action of a high voltage and high energy pulse creating a heat shock wave thus setting off the EED. There are two types of dielectric breakdown EEDs. One type is when the dielectric being broken down is the

explosive itself, the other type acts more like an ordinary heat transfer system by creating hot spots which set off the EED. [Ref. 28]

2. Transducer Action

As described for dielectric breakdown EEDs, development of hot spots initiates the EED firing. If the available energy can be concentrated, then the device would more often guarantee a successful firing. As seen in Table 19 on page 92 the range for pulse, power, and current cover several orders of magnitudes and coincide with the level of currents induced in EED wires as a result of radar, transient, and EMP effects. It is possible to produce specific EEDs (e.g., ones sensitive to long or short pulses). [Ref. 28]

Deposited Bridge Transducers (DBT), normally made of carbon, exhibit a higher resistance than most metal filament transducers thus it is more sensitive to electrostatic energy. Also with current flow there can be a change in the resistance. Table 19 on page 92 gives a hypothetical comparison of three EEDs. Note the sensitivity of the DBT to capacitor discharge energy and constant current but, much less sensitive in terms of voltage. Table 19 on page 92 also illustrates the different ways for EED discharge which are:

- Constant Current when $E_1 = \int I_c^2 R dt$
- Constant Voltage when $E_2 = \int \frac{V_c^2}{R} dt$
- Capacitance Discharge when $E_3 = \frac{1}{2} CV^2$

where

R = instantaneous EED resistance

I_c = constant current

t = time

V_c = constant voltage

C = capacitance.

There are two types of conditions under which EEDs can fire adiabatically and non-adiabatically. For the adiabatic case the current pulse is delivered in a time much less than the time constant τ thus the ohmic heat has not had a chance to dissipate. The general heat equation is extensively discussed in the Analysis chapter.

D. TYPES OF INITIATIONS

There are many types of energy sources capable of posing a threat to prematurely setting off an EED such as:

- electrical connected circuitry (ECC)

- electromagnetic radiation (ER)
- electrostatic discharge (EC)
- mechanical (M)
- heat (H)
- chemical (C).

Examples of ECC may include exposed sources, stray currents, or potential differences between grounds. In ER some of the factors causing EED sensitivity to EM radiation are:

- field intensity
- frequency (particularly the resonance frequency)
- pulse length and pulse repetition rate (which determine whether the process is adiabatic or not)
- reflections (which contribute to amount of absorption)
- antennas and EED orientation (which affects amount of EM current inducement into the wires)
- EED and circuitry effectiveness for reception of EM radiation (as a function of gain and amount of hardening)
- EED sensitivity (which is a function of the specific design).

The ER from other sources (e.g., radio, TV stations, short wave radio, etc....) are a constant unwanted initiating source for EEDs. EEDs with loop and dipole circuitry act as very good receivers when exposed. Table 20 on page 93 gives some safe distances necessary for EEDs from RF sources. Another potentially dangerous source comes from the personnel working with the ordnance that contains EEDs or with EEDs themselves. Some of the factors include:

- type of floor
- floor resistance measuring method
- outer garment material
- position of person (i.e., walking, sitting, or scuffing).

NAVORD 10773 [Ref. 28] completely explains the above premature causes of EED initiation.

VI. TESTING

A. TEST CONDITIONS

In 1966 a HERO weapon evaluation test procedure was outlined in order to complete testing in a predictable concise manner. This procedure is outlined in reference 35.

B. PARAMETERS AND RESULTS

In the beginning the missiles were being tested using the go/on go method. This means that the EEDs actuated or not. The EEDs were made inert and maintained in their normal configuration. In this method if the EED actuated, then there is clearly evidence of hazard but, if it does not fire there is no real useful information. If a statistically valid sample were run this test would be too expensive. The testing steps involve:

- remove explosive material
- replace EED with initiator
- turn on shipboard transmitters
- examine EED to see whether it had exploded.

The EEDs that initiate the weapon are loaded in their normal configuration with all explosive charges and propellants removed.

Another method with an instrumented EED was used with greater success. The instrumented EED was composed of an inert EED with a thermocouple and was placed in the ordnance. It was properly shielded so that it would not be affected by RF radiation. This new device made it possible to measure the EED induced current in terms of the ohmic heating of the bridgewire. The level of current HERO testing is interested in is called the ***No Fire Current Rating*** and is defined as:

> ... the direct current sensitivity of an EED based on a specified threshold probability of initiation. [Ref 13]

The probability is normally set at four standard deviations below the 50% probability value.

Before testing an ordnance on the ground plane the following information must be available:

- the maximum no-fire current (MNFC) of the EED
- the frequency or power level the ordnance is to be tested at
- sensitivity of the recording instrumentation
- available power level.

It is often possible that the required testing power level is higher than the available power level. Under these conditions either the reading instrumentation will not detect a current. If a current is detected then as seen in the ***TESTING*** chapter the calculation of the % MNFC is obvious. If a current is not detected then it is assumed that the induced current is only slightly less than the MDC of the instrumentation. This calculation is also done in the ***TESTING*** chapter.

By the end of 1960, there were four well described HERO tests and procedures which are the following:

- laboratory tests done at the ground facility
- field tests (weapon testing on board ships)
- Go No-Go tests (uninstrumented EEDs)
- instrumented tests (instrumented EEDs with thermocouples).

Go No-Go tests do not prove to be very cost effective and have proven to take too much time. In this type of test the EEDs are outfitted with explosive beads and then put into the rocket motor or ordnance. This device is exposed to the RF environment and either the EED explodes or not. If the go no-go test were repeated 30 times and none of the EEDs exploded, then this would not be conclusive proof that one will not fire on the 31st time. For a 95% confidence level the actual failure rate might be less than 10%. In conclusion, 30 repetitions is statistically not enough to define a weapon as being ***HERO Safe.*** [Ref. 29]

Figure 37 on page 118 gives an example of a MNFC calculation. For a particular case the calculated MNFC may be above the 15% safety level, but the weapon tested still could have a HERO SAFE ordnance classification if the testing engineers have a sufficient knowledge of this particular weapons environment and other factors.

The Maximum Allowable Environment (MAE) per frequency band is the safe environment necessary for weapons that exceed the safety and/or reliability RF environment amounts. The engineer would have to spell out any restrictions to the EME(e.g., turning off certain types of radar etc....) necessary when storing, moving, or loading that particular weapon. Below is a sample calculation of the MAE.

Given:

-The Test Environment (TE)

-in V/M for communication frequency

-in mW/cm^2 for radar frequency

-% MNFC

-The weapon HERO criteria

-15% MAE_s for safety

-45% MAE_r for reliability

MAE_s= 15/% MNFC x TE

(for Communication frequency measured)

$MAE_r = 15 / MNFC^2 xTE$

(for Radar frequency measured)

MAE_s= 45/% MNFC x TE

(for Communication frequency measured)

$MAE_r = 45 / MNFC^2 xTE$

(for Radar frequency measured)

A number of factors contributed to the origins of the 15% MNFC for safety and 45% MNFC for reliability criteria. Calculations show that a resonance frequency error could result in a current 2.6 times that for the frequencies on either side of it. Other factors contributing to a 15% MNFC safety level include:

- the impedance of a crew member's body
- weapon-to-weapon differences and tie-down chains
- the unpredictability of the aircraft-to-deck voltage. [Ref. 15: p. 5-2]

1. Bruceton Test

The Bruceton test is an experimental procedure developed by the Explosive Research Laboratory used to determine the sensitivity of bulk explosives. The test procedure consists of dropping a weight at a known height onto an explosive. If the explosive did not explode then the weight was increased until the material exploded. The testing is then concentrated in this area. In the testing of EEDs a current sent through a wire instead of weights being dropped. A maximum no fire stimulus is defined as:

> ...the greatest stimulus which does not cause initiation within 5 minutes of more than 1.0% of all electrical initiators at a level of confidence of 95%.

It is given that 50 initiators are to be tested. The five minute rule appears to be arbitrary. [Ref. 15: p. 3-6]

In order to ensure personnel safety it has been judged that 15% of the MNFC would be adequate and 45% of the MNFC would be appropriate to ensure reliability of the ordnance for proper use. These standards are quite arbitrary and are still a matter of debate. [Ref. 15]

2. One Shot Test

The testing method for **one shot** items involves using the ***test to failure*** concept in order to establish a reliable margins of safety. This method has the advantage of requiring a relatively small number of trials in order to secure the desired standard deviation and confidence. In addition, this method is flexible in that it can be employed for a larger range of experiments (e.g., rocket motors, switches, relays, etc....). By testing to failure the lower limit behavioral stress can be observed and a safety margin (σK) can be set where the larger the K value, the greater the reliability of the specimen. This method assumes that the life time of a specimen under stress survives long enough to calculate failure. If the lifetime is too short, then only the stress level can be evaluated. The EEDs fit into this category and are thus called one-shot items.

It is assumed that there is a current just adequate to fire the EED as well as currents (1) to ensure a fire every time, and (2) just inadequate to fire the EED. It is also assumed that the range of distribution for adequate fire is gaussian and that all inadequate current levels will not fire the EED.

Given the above assumptions the exact cause of failure is not important in order to determine the safety margin which becomes an important advantage. Another important advantage of the EED (i.e., initiation temperature or maximum current or voltage before discharge). Only as few as 15 to 20 one-shot items are necessary for a complete experiment.

The one-shot test is a three step process:

- establish the acceptance (or failure) criteria (EAC)
- determine the test interval (DTI)
- select the stress level (SSL). [Ref. 30]

It is critical that EAC is accomplished carefully and accurately to ensure success in the test. A complete list of all methods causing or aiding in unacceptable performance should be carefully and completely investigated . Included in this list should be modes of failure, tolerance limits of the item, and undesirable responses all of which cause

deviation from the items preferred arena of performance. Establishing such failure criteria correctly is the first step to guarantee credibility in the one-shot results.

For DTI the determination of the test interval proves the statistical validity of the method. As a rule the test results at the endpoints, which determine the test interval, should be consistent for any sample size of items. If the lower endpoint is defined as giving a successful item operation and the upper endpoint a failed operation, then stress convergence toward the lower limit would prove to be statistically unsatisfactory because the lower limit would not have been reached. However, if the stress levels converge toward the upper limit it could be assured that lower safe limit had been reached.

Now that the criteria and interval procedures are complete, it is now time to describe how the testing stress is selected. The testing stress is the item selected from the criteria list which could affect performance. The first stress level would naturally be half way in between the two endpoints. A good statement to describe picking of the stress levels states:

> The general rule for obtaining the $(n+1)^{st}$ stress level, having completed n trials is to work backward in the test sequence, starting at the n^{th} trial until a previous trial (call it the p^{th} trial) is found such that there are as many successes as failures in the p^{th} through the n^{th} trials. The $(n+1)^{st}$ stress level is then obtained by averaging the n^{th} stress level with the p^{th} stress level. If there exists no previous stress level satisfying the requirement stated above, then the $(n+1)^{th}$ stress level is obtained by averaging the n^{th} stress level with the lower or upper stress limits of the test interval according to whether the n^{th} result was a failure or a success. [Ref. 30]

Figure 38 on page 118 is an example of a one shot test and results. Note that after the 5^{th} trial, which was a success, there could not be an even number of success and failure tests and the 6^{th} trial became an average of the 5^{th} trial plus the upper limit. The upper limit was chosen because the 5^{th} trial was a success.

With the given stress levels and outcomes, the mean (μ_e), standard deviation (σ_e), and the likelihood ratio (λ) are determined. The likelihood ratio determines whether the sample of tests is statistically acceptable. After determining the μ_e and σ_e, they are corrected for bias. By using the maximum likelihood equations which are:

$$p(\mu_e, \sigma_e) = \sum gh = 0 \tag{66}$$

$$q(\mu_e, \sigma_e) = \sum tgh = 0 \tag{67}$$

where

$$t = \frac{s_i - \mu_e}{\sigma_e} \qquad \textit{normalized stress deviation} \tag{68}$$

$$g = 2x^{-\frac{1}{2}} e^{-\frac{t^2}{2}} = \qquad \textit{Gaussian ordinate for } t \tag{69}$$

$$h = \frac{u}{(1 - G)} - \frac{(1 - u)}{G} \qquad \textit{outcome weighting parameter} \tag{70}$$

$$G = \int_{-\infty}^{t} g\,dt. \tag{71}$$

The letter x is equal to a random sample of N observations where each sample is an independent random variable in a Gaussian distribution. By using an approximation for μ_0 and σ_0, which is a straight calculation, $\Delta\mu$ and $\Delta\sigma$ can be determined and estimates of μ_e and σ_e are calculated. Now the unbiased standard deviation is given by:

$$\sigma = \frac{\sigma_e}{\beta} \tag{72}$$

where β is less than 1 and determined by many computer runs [Ref. 30 : Section 5]. β approaches 1 as N approaches ∞ where σ is the true population σ when $N \rightarrow \infty$. Next variances of μ_e and σ_e are calculated from a chi-square distribution and confidence levels are established. Reference 30 in sections 4 and 5 give a detailed description of the step by step process from determining the μ and σ to calculating the likelihood ratio and comparing it against a prechosen critical level as a test for lot acceptance.

VII. ANALYSIS

A. HEAT FLOW EQUATIONS

Up to this point the HERO an EMP phenomena have been discussed in regards to the impact on the fleet ordnance and weapons systems. The hardening of ordnance and these systems by various means have also been discussed as well as current HERO and EMP testing procedures on EEDs. The question how these two different phenomena can be related. One remaining fact to note is that EEDs are initiated or detonated when the EED's temperature rises to a particular degree. This ohmic heating phenomena is not dependent on any particular time or shape of a current function but relies on basic heat flow dynamics.

The electrothermal parameters of the EEDs are not exact values and at best can be described in terms of averages. It is seen that variations can occur with individual EEDs, environment of testing, and material on the bridgewire [Ref. 31]. It is assumed that these fluctuations are sufficiently small as to be insignificant. The basic differential heat flow equation governing the conversion of current to bridgewire heating is:

$$[C_P \frac{d\theta}{dt}]_{\varepsilon} + [Y\theta]_h = P(t) \tag{73}$$

where

C_P = heat capacity

Y = heat loss factor

θ = bridgewire temperature above ambient

P(t) = power level of electrical signal

$[]_{\varepsilon}$ = thermal energy used in wire

$[]_h$ = heat flow away from wire.

For wires with a coefficient of resistance α:

$$R_t = R_O(1 + \alpha\theta) \quad \rightarrow \quad \theta = \frac{R_t - R_O}{\alpha R_O} \tag{74}$$

where

R_O = initial wire resistance. [Ref. 28]

Friday [Ref. 32] states the general heat flow equation representing joule heating of EEDs as:

$$\theta(t) = \theta_a + P(t)R(1 - e^{\frac{-t}{\tau}});\ t > 0 \tag{75}$$

where

$\theta(t)$ = temperature as a function of time (^oC)

θ_a = ambient temperature (^oC)

t = time of current flow (sec)

P(t) = $I^2(t)R_e$ (watts) = power due to heating

R_e = EED electrical resistance (ohms)

R = thermal resistance or thermal gradient (^oC/ Watts)

τ = RC_p = thermal time constant.

Here the equation is stated in terms of the ambient temperature and is the differentiated form of the above equation. When t >> τ, a steady state temperature will be established. This gives a rise in temperature rate and cooling equation of:

$$\frac{d\theta(t)}{dt} = \frac{P(t)}{C} e^{\frac{-t}{\tau}} \quad \textit{temperature rise} \tag{76}$$

$$\theta(t) = \theta_a + (\theta_O - \theta_a)e^{\frac{-t}{\tau}};\ P(t) = 0 \quad \textit{cooling equation} \tag{77}$$

where

θ_O = initial temperature.

This equation shows an exponential cooling of the EED bridgewire. It is important to mention that if the explosive mixture characteristics are easily changed prior to the bridgewire reaching the critical temperature, then the critical temperature may increase beyond the ability of the EED and dudding results. These changes could occur if P(t) is a pulse type or minimal function only resulting in a sub-critical bridgewire temperature but high enough to produce dudding. [Ref. 32]

If t << τ, the rise in temperature rate equation becomes:

$$\frac{d\theta(t)}{dt} = \frac{P(t)}{C_p} \quad \rightarrow \quad \theta = \int \frac{P(t)dt}{C_p} dt, \tag{78}$$

becoming essentially an adiabatic process. If the function P(t) is a series of pulses either periodic or not, the cooling equation above would be used in this case as well, assuming

the cooling time between pulses $\simeq\tau$. This would require using a combination of adiabatic and non-adiabatic equations. This phenomena is known as ***thermal stacking*** and is illustrated in Figure 39 on page 119. Because this is an adiabatic process, there is no heat loss and there exists a peak pulse power amplitude which is sufficient to initiate an EED. The energy of this pulse is the area under the curve of a power versus time diagram. Assuming a rectangular pulse the energy calculations are:

$$U_f = PW \tag{79}$$

where

W = pulse width in seconds

U_f = energy to initiate EED with a single pulse (joules)

P = peak power = $I_f^2 R_e$.

From the above equation, the thermal capacity can be calculated as:

$$C_P = \frac{U_f}{(\theta_c - \theta_a)} \tag{80}$$

and also it shows that the temperature rise is proportional to the pulse energy. For a loaded EED (e.g., squib MK1) some typical thermal constants are:

$C_f = 2.7x10^{-6}$ watts-sec °C

R = 1.471 °C milliwatt

τ = RC $\simeq$ 4000 microseconds. [Ref. 33]

γ = 600 microwatts °C

C_P = 2.4 microjoules °C

The firing temperature for a Squib MK1 is 700°C. [Ref. 33]

If there is a steady power level supplied to the bridgewire with temperature proportional to t giving:

$$\theta = \frac{I^2 R_e}{C_P} t, \tag{81}$$

eventually an equilibrium will be reached and then $\frac{d\theta}{dt} = 0$. The steady state temperature would then be:

$$\theta = R_e P(t) \tag{82}$$

where

$$P(t) = \frac{I^2}{\gamma - I^2 R_e \alpha} . \tag{83}$$

Now if the resistance is temperature dependent then:

$$R_e = R_O(1 + \alpha\theta) \tag{84}$$

where α is the temperature coefficient of resistivity $(\frac{\Omega}{\Omega - {}^\circ})$. For a Squib MK 1 MOD 0 α = .0008. [Ref. 33]

If the current I can be assumed to be a constant and the temperature coefficient of resistivity (α) in linear, then the P(t) function is derived as:

$$P(t) = I^2 R(1 + \alpha\theta).$$

This would give a basic heat flow equation of:

$$C_P \frac{d\theta}{dt} + \theta(\gamma - I^2 R\alpha) = I^2 R.$$

The solution to this differential equation is:

$$\theta = (\frac{I^2 R_e}{\gamma - I^2 R_e \alpha})(1 - e^{\frac{-t}{\tau'}}) \tag{87}$$

where

γ = 1 R

$\tau' = \frac{C_P}{\gamma - I^2 R_e \alpha}$.

Then the maximum temperature would be:

$$\theta_{\max} = \frac{I^2 R_e}{\gamma - I^2 R\alpha} = \frac{I^2 R_e}{\gamma'} . \tag{88}$$

Note that if γ' approaches 0 or t < < τ', then:

$$\theta = \left[\frac{I^2 R}{\gamma - I^2 R\alpha} \right]\left[\frac{t}{\tau} \right] = \frac{I^2 Rt}{C_P} . \tag{89}$$

In the case where there is no heat loss the system (bridgewire and current) can also act like a capacitor discharge firing where:

$$P(t) = \frac{dE}{dt} = \frac{q}{C}\frac{dq}{dt} = iV \tag{90}$$

and

$E = \frac{Q^2}{2C}$

C = capacitance of the capacitor

V = instantaneous voltage

Q = initial charge.

This gives a temperature rate change and solution of:

$$\theta(t) = Q_2^2 - \frac{q_{(t)}^2}{2} C_P C \tag{91}$$

where

$$q = Qe^{\frac{-t}{R_e C}}. \tag{92}$$

Now the original heat flow equation becomes:

$$C_P \frac{d\theta}{dt} + \gamma\theta = \frac{V^2}{R_e} e^{\frac{-2t}{R_e C}}. \tag{93}$$

If it is assumed that R_e = constant, this give:

$$\theta = \frac{CV^2}{2C_P(\frac{R_e C}{2\tau} - 1)} (e^{\frac{-2t}{R_e C}} - e^{\frac{-t}{\tau}}). \tag{94}$$

Also the time to reach a maximum temperature (again still assuming no heat loss) is:

$$t_{\max} = \frac{1}{\frac{2}{R_e C} - \frac{1}{\tau}} \ln(\frac{2\tau}{R_e C}) \tag{95}$$

and the maximum temperature would become:

$$\theta_{\max} = \frac{CV^2}{2C_P} e^{\frac{-t_{\max}}{\tau}}. \tag{96}$$

So by manipulation of the basic heat flow equation, an appropriate equation can be derived to cover a specific type of EED or condition of firing (e.g., EMP or HERO

effects). With information on the Squib MK1 MOD 0 EED collected from NSWC, Figure 49 on page 127 gives some sample calculation results using the maximum temperature equations for long and short time intervals. For this particular EED it is assumed to fire at 700°C at a constant current [Ref. 33]. Obviously all current functions are not linear but nevertheless the answers are close to what would be predicted. The constants and therefore the resulting answers are very rough estimates but are close enough to warrant further study using accurate values and running a full scale simulation. In the case of HERO the equations seem to work better possibly due to the lack of many nonlinearities as in the EMP case.

B. TRANSFER FUNCTIONS

1. EMP pickup

Determining the currents and voltages produced by the EMP generated electric and magnetic fields is quite difficult for all but the most simple of geometries of collectors. Unfortunately the collectors usually behave in a nonlinear fashion. In order to simplify this problem the ***thevenin equivalent circuit*** concept has been greatly used. This involves characterizing the transfer phenomena by an equivalent voltage generator or impedance source. The source voltage and impedance are a function of arrival angle and collector geometry. When the collectors are small compared to the wavelength ***quasistatic case*** characterization is quite simple, but when they are greater than or equal to the wavelength size, characterization is much more complexed. Under this situation a ***lumped parameter*** representation is used where the collector system is reduced to a circuit analysis problem. Computer codes such as SCEPTRE and CIRCUS are used to analyze such a nonlinear circuit outlay. [Ref. 2: p. 35]

When determining EMP transfer to voltage and current two mathematical approaches are used:

- frequency domain analysis using LaPlace or Fourier transform
- time domain analysis.

These equations can either be solved by hand or computer codes as mentioned above. The codes can be used if the problems can be modeled as lumped electrical parameters. In this figure the antenna is modeled as having a two terminal network output with a thevenin equivalent voltage and source impedance (measured or theoretical).

By means of Fourier analysis the time domain of the wave form can be transformed to the frequency domain by:

$$E_i(j\omega) = \int_{-\infty}^{\infty} E_i(t)e^{-i\omega t}. \tag{97}$$

By circuit analysis using $E(j\omega)$ the output voltage is developed. Once again Ricketts [Ref. 2: p. 48] shows that by using Fourier analysis the voltage time domain can be deduced:

$$V_2(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} V_2(j\omega)e^{j\omega t}d\omega. \tag{98}$$

System nonlinearity occurs as a result of electronic systems containing vacuum tubes, diodes, and transistors. The nonlinearity (which includes hysteresis effects) can be most effectively solved by the above mentioned computer codes as long as the collector system can be represented as lumped parameters (e.g., resistors, capacitors, and inductors). Figure 40 on page 120 gives an example of the lumped parameter nonlinear (LPN) method using the Fourier Transform method (FTM) for a 45° angle of arrival. Figure 41 on page 120 gives the equivalent lumped parameter circuits for the first two resonances. In this figure there is one circuit to synthesize the variation of effective height with frequency and the other to generate the output impedance. [Ref. 2]

In Waters [Ref. 34] for security reasons a true and classified electric field vector function was not obtainable, but an unclassified function for the electric field vector is:

$$E(t) = E_o e^{-at}\sinh(bt) \qquad V/M \tag{99}$$

where a and b are rise and decay time constants and E_o is the peak electric field or

$$E(t) = \frac{1}{2}E_O\left[e^{(-a+b)t} - e^{(-a-b)t}\right] \qquad V/M. \tag{100}$$

When solving for a and b, assuming that the rise time (τ) is < < the decay time (T), then:

$$a = \frac{(\frac{k}{2T})[2e^{\varepsilon} - 1]}{e^{\varepsilon}} - 1 \tag{101}$$

$$b = \frac{\frac{k}{2T}}{e^{\varepsilon} - 1} \tag{102}$$

where

$$\varepsilon = \frac{k\tau}{T}. \tag{103}$$

By assuming a plane wave for the EMP wave and using the Poynting vector, the power density (P(t)) is:

$$P(t) = \frac{E^2(t)}{120\pi} \qquad (\frac{W}{m^2}). \tag{104}$$

By integrating over time the total pulse energy per unit area (Q) is:

$$Q = \int_0^\infty P(t)dt = \frac{E_o^2}{480\pi}\int_0^\infty e^{-2at}\sinh^2(bt)dt = \frac{E_o^2 b^2}{480\pi a(a^2 - b^2)} \qquad (joules/m^2). \tag{105}$$

The type of filter used in the circuit design does significantly determine the amount of pulse energy being transmitted. For low-pass, high-pass, and band-pass filters, there are equations which calculate what fraction of the total pulse energy able to pass through the filter or the amount of energy contained in the particular region. The validity of these equations come into question because an EMP contains a broad band of frequencies and is an EM wave and not a current source per se. Figure 42 on page 121 shows the equations for these filters and serve to explain this phenomena. Also note that Table 21 on page 93 gives some typical energies necessary to cause some type of malfunction within particular devices. Only a small amount of joule energy is necessary to cause upset and burnout. These numbers are consistent with the figures in Table 15 on page 90 and again show the resistance of vacuum tubes to burnout. [Ref. 34]

2. HERO Transfer

In the HERO chapter electric energy transfer was discussed in terms of a uniform field disregarding the type of antenna used in the energy transfer. In this chapter a generic equation can be arrived at and is reported as:

$$I = \sqrt{\frac{G_R G_T W_N \lambda^2}{(4\pi r)^2 R}} = \sqrt{\frac{G_R P_A \lambda^2}{(4\pi R)}}. \tag{106}$$

The amount and type of current induced in wires leading to an EED depends on the type of antenna receiving. There are three basic types of antennas to be discussed which are:

- Loop Antenna
- Dipole Antenna
- Toploaded Monopole Antenna.

These equations are valid for a frequency range up to 32 MHz and assume that the EED lead wires are made of copper. Also factors related to ground effects (e.g., reflection and grounding) are not considered. The factors relating to current induction in antennas has been narrowed to the following:

- Antenna dimensions
- EED resistance
- Impedance position
- frequency. [Ref. 35]

a. Loop Antenna

As noted in Figure 43 on page 122 a loop antenna can be formed by wires that are in direct contact with each other (e.g., soldered wires) or wires that have a capacitive contact (e.g., twisted or braided wires). This twisted and braided wire influence cannot be neglected because it can act as a capacitor eventually discharging a current.

The basic equation for current induction is:

$$I = \frac{V_i}{\Sigma R} \tag{107}$$

where $\sum R$ is the sum of all of the resistances and V_i is the induced voltage. The law of induction states that the voltage is equal to the magnetic flux. This gives the equation:

$$V_i = A\frac{dB}{dt} = A\mu_o\frac{dH}{dt} \tag{108}$$

where A equals the area of the loop. If sinusoidal time variations only are considered, then:

$$V_i = A\mu_o\omega H = \frac{D^2\pi\mu_o\omega E}{4Z_O} \tag{109}$$

where

D = diameter of the loop antenna

E = electric field intensity

H = magnetic field intensity

$Z_o = 120\pi\ \Omega$ (wave impedance of free space).

Now the sum of the resistances is equal to:

$$\sum R = R_R + R_{EED} + R_w + R_L \tag{110}$$

where

R_R = radiation resistance of the loop

R_{EED} = EED resistance

R_w = ohmic losses

R_L = tuning capacitor losses.

Schwab in Ref. 35 formulates the equation for the above resistances. For R_R the equation is:

$$R_R = 197\left(\frac{\pi D}{\lambda}\right)^4 + 686000\left(\frac{\pi D}{\lambda}\right)^8 \quad (\Omega)\ ;\ \frac{\pi D}{\lambda} \leq 0.35 \tag{111}$$

where λ equals the free space wavelength. For a small $\frac{\pi D}{\lambda}$, the formula would drop the 8th power component. A first order approximation for R_w gives:

$$R_w = \frac{D\pi}{d\pi\sigma x_o} \tag{112}$$

where d is the wire diameter and

$$x_o = \sqrt{\frac{2}{\sigma\omega\mu}} \qquad (skin\ depth). \tag{113}$$

This gives a final first order equation of:

$$R_w = \frac{D}{d}\sqrt{\frac{\omega\mu}{2\sigma}}. \tag{114}$$

Ref. 35 derives an approximation for R_L giving:

$$R_L = \frac{\left[120\pi\left(\frac{\pi D}{\lambda}\right) + 15500\left(\frac{\pi D}{\lambda}\right)^4\right]\ln\left(\frac{D}{d}\right)}{Q}\quad \Omega \tag{115}$$

where Q is defined as, "... quality factor of a lossy reactive element...." and comes as a result of the twisted or braided wire ends. Figure 44 on page 123 is an example of how

current is influenced by frequency and EED resistance while Figure 45 on page 124 shows the influence of the loop diameter.

b. Dipole Antenna

A dipole antenna has a different configuration than a loop antenna as seen in Figure 46 on page 125 with a linear sloped current distribution as seen in Figure 47 on page 125. If we assume that the dipole is oriented for maximum pickup then the open circuit voltage becomes:

$$V_i = h_e E \tag{116}$$

where

$$H_e = L_D\left[1 + (\frac{L_D}{\lambda})^2\right]\frac{1}{2} \;;\quad \frac{L_D}{\lambda} \leq 0.5 \tag{117}$$

and is called the effective dipole length. The resistances for a dipole are the following:

$$R_R = 5(\beta L_D)^2 + 0.24(\beta L_D)^4 \ (\Omega)\,;\quad \beta \leq \frac{\pi}{L_D} \tag{118}$$

$$R_w = \frac{L_D}{\pi d}\sqrt{\frac{\omega\mu}{2\sigma}} \tag{119}$$

$$R_L = 0.6\left[\ \ln(\frac{L_D}{2d})\cot(0.52\frac{2\pi}{\lambda}L_D)\right] \tag{120}$$

where Q is equal to 200. Note the similarity between R_w for a loop and dipole. The curves for current as a function of frequency are similar in shape to those for a loop antenna. When R_{EED} increases the peak current for any given frequency is reduced and the current also decreases with an increase in frequency for frequencies greater than 20 MHz.

c. Toploaded Antenna

A toploaded antenna is formed when a metallic object has a much larger horizontal component than vertical. Aircraft and missiles are perfect examples of toploaded antennas. The craft acts as an antenna when a wire connected to an EED makes ground contact. Information concerning toploaded antennas is empirically determined due to the oddity of design of the missiles or aircraft. But as the case with the other two types of antennas, the higher the R_{EED}, the lower the induced current.

Schwab [Ref. 35] gives several comparisons of the three types of antennas. The loop antenna has a maximum current in the 10 to 30 MHz range while an increase in radiation causes an increase in resistance which in turn reduces the current. This is also true for dipole antennas. For the dipole antenna, current increases with dipole length as an increase in loop diameter increases it's current. In comparing all three types of antennas, the toploaded monopole will fire much easier for a particular EED than the other two. The loop antenna records the highest current for EED firing. [Ref 35]

C. COMPARISON

By working through the transfer functions and heat flow equations, it is possible to compare EMP levels with HERO levels involving weapons protection. From the heat flow equations the firing temperature of the EED can be calculated. If the premise is true that EED firing is purely based on ohmic type heating, then comparison of these two programs come down to some basic steps. One approach might be:

- Determine the EMP threat (e.g., 10,000 V/M)
- Use the transfer function to determine the current function
- Use the adiabatic heat flow equations to get a temperature function (i.e., temperature as a function of current) and a maximum temperature
- Given a maximum temperature, use the HERO heat flow equations to derive a current function
- Plug this current function into the HERO transfer function to arrive at a power density around an antenna or with sufficient information, power density at the source.

An appropriate code incorporating SCEPTRE or CIRCUS could be generated including various types of radar waveforms to come up with an equivalent HERO level for a given EMP. Thereby testing a weapon for EMP, the appropriate HERO level can be set and compared against already exsisting HERO standards. Better yet, by determining the needed power by an EMP to fire a particular EED, and thus set 15% and 45% MNFC levels, and equivalent HERO current can be set along with the safety and reliability standards. Figure 48 on page 126 shows a scheme of the above.

It appears that the best function in comparing an EMP to the induced current comes from computer codes mentioned above Due to nonlinearities investigators found it too difficult and time consuming to do the calculations by hand. These current functions resemble damped sinusoidal waves of short duration. It is possible that his function could be approximated to just a damped wave. Depending on the circuitry associated with a particular temperature equation can be used for either a capacitor type

discharge of current or for a conservative constant current pulse. These equations can be found in the earlier part of this chapter. By making conservative approximations, a maximum temperature can be generated. By knowing the thermal and electrical constants and by using the peak temperature from the EMP heat flow equations, a constant current can be derived. With an equivalent current (i.e. equivalent to a particular EMP) voltages and EM fields can be arrived at via the equations earlier discussed.

VIII. CONCLUSION

A detailed description of the EMP and HERO programs has been given. The EMP and EM radar radiation phenomena as well as the protection against these phenomena have been thoughly investigated. Hardening of weapon systems and the EED are common areas of interest for these programs as it is their charter to protect weapon systems and ordnance from radiation. Each program has a different type of radiation to contend with but both relate to the ordnance via the EED and ohmic heating of the EED to initiate detonation of a device. This sphere of commonality leads to a logical conclusion of combining, if not all, at least certain areas within the EMP and HERO program. Some of the benefits of combining the two programs include:

- Simultaneous qualification of all weapon systems and ordnance for any EMV, EMI or EMC problem
- Simultaneous inspection and survey of ships and other platforms for HERO and EMP safety
- A large overlap in hardening techniques would require less duplication of effort
- United representation on the EMCAB to alleviate EMP and HERO problems in the design phase of the procurement process
- Only one set of instructions and standards would have to be promulgated
- Only one set of safety standards covering all EM radiation including transient radiation
- Only one set of certification criteria for ship surveys
- Ensures only one nomenclature
- Best testing methods can be adopted ensuring reliability of data
- Leads the way for incorporation of transient radiation and future forms of EM radiation hazards to ordnance and weapon systems.

Given the reliability of equations in the previous chapter, it is possible to show the equal comparison between a wire current produced as a result of an EMP and Radar by simply equating the maximum temperature produced by each phenomena. What is worked out via the equations can simply be tested by comparing empirical data for the MNFC versus the theoretical MNFC results. This of course assumes that the equations themselves are valid. By taking experiment further the question must be asked if an EMP level can be translated into an equivalent HERO level? If so would this result in a modification of the present HERO standards?

One question arising is what effect would off axis Bremsstrahlung radiation from a charged particle beam have on EEDs and weapon electronics associated with an EED? By using available information on rad(si) per second dose rate levels available from a free electron laser, there may be a high enough current generated within the semiconductor devices to not only cause electronic damage or upset but also EED detonation or dudding [Ref. 30]. Testing of currently available U. S. offensive weapons against this short but very high rad(si) per second dose would be prudent and aid in meeting future design and production needs for weapon systems and ordnance safety, protection, and hardening.

Through a careful search of the literature for theoretical postulation and empirical results equations were found which describe how the EMP and HERO phenomena can be converted into a current. Heat flow equations show how the current can produce ohmic heating in the EED apparatus. If this temperature is high enough, there is detonation. Because the detonation is temperature dependent and not directly current dependent, the two programs have an indelible tie together that can be exploited for the benefit of not only the two groups (EMP and HERO) but also for those that they serve.

APPENDIX A. HISTORY OF EMP

1945 TRINITY EVENT: electronic equipment shielded reportedly because of Fermi's expectations of EM signals from a nuclear burst.

1951-2 First deliberate EMP observations made by Shuster, Cowan, and Reines. Reines proposes several possible mechanisms. Diagnostic and detection capabilities recognized.

1954 Garwin (LANL) estimates prompt gamma-produced Compton currents as primary sources of EMP.

1957 Bethe makes estimate of high-altitude EMP signals using electric dipole model (early-time peak incorrect).

1957 Haas makes magnetic field measurements for PLUMBOB test series (interest in the possibility of EMP setting off magnetic mines).

1958 Joint British U.S. meeting begins discussions of system EMP vulnerability and hardness issues.

1958 Komaneets (USSR) publihes open literature paper on EMP from atomic explosion.

1958 First high-altitude tests TEAK and ORANGE in operation HARDTACK. First indication of the magnitude of the high-altitude EMP signal. The only good measurements were from over the horizon.

1959 Popham and Taylor (U.K.) present a theory of "radioflash".

1959 First interest in EMP coupling to underground cables of Minuteman missle.

1962 FISHBOWL high-altitude tests; EMP measurements driven off scale despite TEAK and ORANGE data.

1962 SMALL BOY near-surface EMP test.

1962 Karzas and Latter publish two open literature papers on using EMP signals for detection of nuclear tests; bomb case EMP and hydromagnetic EMP considered.

1963 EMP hardening of military systems discussed in the open literature.

1963-4 First EMP system tests carried out by the Air Force Weapons Laboratory (AFWL).

1963-4 Longmire gives a series of EMP lectures at AFWL; presents detailed theory of ground burst EMP, close-in EMP, and shows that the peak of the high-altitude EMP signals is explained by magnetic field turning (magnetic dipole signal).

1964 First note in the LASL AFWL EMP notes series published.

1965 Karzas and Latter publish first open literature paper giving high-frequen approximation for the high-altitude magnetic dipole signal.

1965 Underground simulation of EMP discussed by Daley.

1967 Construction of ALECS as the first guided-wave simulator is completed for EMP simulation on missiles.

1967 Ajax underground nuclear test.

1970 Preliminary specifications presented by Schaefer for EMP underground test.

1974 MING BLADE underground EMP test for confirmation of near-surface burst EMP models.

1975 DINING CAR underground EMP test as the first system hardware EMP test.

1975 MIGHTY EPIC underground EMP test.

1978 Special joint issue on the nuclear EMP in IEEE Transactions on Antennas and Propagation and also on Electromagnetic Compatibility.

1978 Nuclear EMP meeting in Albuquerque under IEEEsponsorship.

1980 Large transmission line is installed in AURORA flash x-ray test cell to simulate tactical source region EMP.

1981 Direct electron injection in AURORA test cell gives credible simulation of deep source region EMP.

1982 Nuclear EMP meeting in Albuquerque in conjunction with the IEEE and National Radio Science. [Ref. 37]

APPENDIX B. DEFINITION OF OTHER ENVIRONMENTS

XEMP	When the burst is above 50 kilometers the gamma rays are not as easily absorbed by the atmosphere as the x-rays are absorbed. Therefore at this altitude x-rays are the predominant EMP mechanism.
DEMP	For high altitude bursts the tangent portion of the burst traverses the ionophere in space. The different frequencies travel through the ionosphere at different velocities therefore, the dispersed EMP is different from the original pulse.
MHD EMP	Magnetohydrodynamic EMP. For a high altitude burst the fireball and expanding debris cause perturbations and distortions of the earth's geomagnetic field. The burst ionizes the air around it becoming very conductive both the debris and region. This causes the perturbations of the geomagnetic field which lasts seconds and possibly disrupts long cable systems.

APPENDIX C. TESTING AND SIMULATION FACILITIES

Below is a brief description of some of the important simulators.

ALECS	The first wave guide simulator built in 1967. Used to simulate high altitude bursts with a maximum field of 10 kilovolts per meter.
ACHILLES I	used to simulate high altitude burst on low level systems. Contains a 5 megavolt pulse and also has a vertically polarized electric dipole configuration.
ATHAMA II	Same description as in ACHILLES I.
ACHILLES II	These simulators are a horizontally polarized hybrid and are used to simulate high altitude bursts on low level systems.
ATHAMA I	Same description as in ACHILLES II.
ATLAS I	Used to verify EMP hardening of large aircraft of a high altitude burst. It is a threat level guided wave simulator.
ARES	This is a threat level advanced research EMP simulator with an output peak of 4 megavolts a rise time of 6 nanoseconds and decay of 250 nanoseconds.
EMPRESS	This is a Navy hybrid horizontally polarized simulator for low level ship simulation of high altitude bursts.
TEMPS	This is a transportable EMP simulator for high level ground systems testing against high altitude simulated bursts.
RES-1	This is a radiating EMP simulator used to simulate high altitude bursts for low level testing and is airborne.

APPENDIX D. HISTORY OF HERO AND EEDS

A. HISTORY OF HERO

1880's	Michael Faraday and Heinrich Hertz showed that EMR can induce currents in conducting wires.
1887	Marconi demonstrates use of wireless between ship and shore.
1899	First American Navy message transmitted.
1899	Wireless transmission used in naval maneuvers.
1903	Christian Hulsmeyer developes a primitive collision avoidance radar.
1910	All U. S. Naval vessels carrying 50 or more passengers 200 or more miles are required to have a wireless.
1952	Bureau of Ordnance rescinds regulations governing ordnance safety in a RF field.
1956	First comprehensive HERO test done aboard USS Franklin D. Roosevelt.
1958	A group of engineers, scientists, and technicians assembled at Dahlgren, VA, to prepare testing aboard the USS Cony.
1959	HERO formally organized at Dahlgren.
1959	HERO testing program given official status.
1960	HERO ordnance accidents reported as an "unexplained" cause.
1960	Ground plane designed at Dahlgren, VA.
1960	Money appropriated to build first ground plane.
1960	Basic testing procedures were established and published.
1961	Bismuth-Antimony (Bi-Sb) thermocouple accepted.
1961	Design guide for manufactures of ordnance first published.
1963	Navy HERO program tests all ordnance containing EEDs.
1964	First military specifications for HERO produced (MIL-P-24014).
1965	Bureau of Naval Weapons produced NAVWEP OD 30393, the ***HERO Design Guide***.
1966	NAVSEA responsible for all shipboard and field surveys.
1967	CNO establishes a safety survey team for aircraft carriers.
1972	Second military specifications for HERO produced (MIL-STD-1385A).

1981	Instruction for existence and continuation of HERO program originates (OPNAVINST 8023.2C).
1982	Third military specifications for HERO produced (MIL-STD-1385B).
1985	CNO promulgates OPNAVNOTE 5100 limiting personnel exposure to EM energy.
1987	Commander, NAVSEA Systems Command recognizes HERO Program with NAVSEAINST 8020.7B. [Ref. 15]

B. HISTORY OF EED

1745	Doctor Watson of the Royal Society of England exploded black powder with an electric spark.
1750	Ben Franklin improved on Watson's demonstration by compressing the black power in a case.
1830	Moses Shaw patented the electric firing of black powder (gunpowder) by an elecrtric spark through fulminating silver and gunpowder.
1831	William Bickford invented the safety fuze and built a factory in Cornwall, England.
1830-1832	Dr. Robert Hare developed bridgewire method of electrical blasting.
1864-1867	Alfred Nobel developed a method of initiating nitroglycerin by using safety fuze initiating, black powder ignitors and later capsules of mercury fulminate, the first commerical detonator.
1870's	H. Julius Smith successfully introduced bridgewire initiated electric blasting caps and developed a portable, generator-type blasting machine.
1895	Delay electric blasting caps utilizing safety fuze as the delay train, introduced by H. Julius Smith.
1913	"Cordeau" detonating cord introduced into the United States.
1926	Du Pont replaced mercury fulminate with tetryl as the base charge in its blasting caps.
Late 1920's	Vented delay electric blasting caps with internal delay train and greater uniformity introduced.
1930's	Replacement of mercury fulminate in ignition and primer charges was begun with the use of a variety of more stable explosive compounds.
1930's	Ventless delay caps introduced.
1937	Detonating cord with PETN in a fabric braid developed, replaced "Cordeau" cord.

1940's	Plastic replaced cotton yarn/enamel as insulation for electric blasting cap leg wires and improved sealing of electric blasting caps with rubber plugs appeared.
1940's	Tetryl replaced by PETN as cap base charge.
1946	Short-interval delay electric blasting caps introduced having delay intervals in milliseconds rather than seconds.
1948	Use of capacitor discharge type blasting machines began replacing a major share of the generator types with safer and more reliable power units.
1950	Delay connectors for detonating cord developed providing a relatively precise delay of the detonating cord.
1960	Low-energy detonating cord introduced which led to improved nonelectric detonating systems.
1976	Nonelectric delay caps introduced, which provided improved timing and reduced noise levels. [Ref. 15]

APPENDIX E. EME LEVELS

The following tables are Electromagnetic Environmental Levels from 1972 to 1986.

Table 1. ELECTROMAGNETIC ENVIRONMENTAL LEVELS OF MIL-STD-1385, 1972: [Ref. 15]

Frequency (MHz)	Field Intensity [V(rms)/m]	Average Power Density (mW/cm^2)
Communications		
0.25 - 0.535	300	-
2 - 32	100	-
100 - 156	-	0.01
225 - 400	-	0.01
Radars/Other Electronic Equipment		
200 - 1215	-	10
1215 - 1365	-	5
2700 - 3600	-	78
5400 - 5900	-	105
7900 - 8400	-	175
8500 - 10400	-	150
33200 - 40000	-	4

Table 2. ELECTROMAGNETIC ENVIRONMENTAL LEVELS OF MIL-STD-1385, 1982: [Ref. 15]

Frequency (MHz)	Field Intensity [V(rms)/m]	Average Power Density (mW/cm^2)
Communications		
0.25 - 0.535	300	-
2 - 32	100	-
100 - 156	-	0.01
225 - 400	-	0.01
Radars/Other Electronic Equipment		
200 - 225	-	20
400 - 850	-	15
850 -950	-	55
950 -1400	-	10
2700 - 3600	-	200
5400 - 6000	-	400
7000 - 7900	-	30
7900 - 8400	-	175
8400 - 11000	-	400
11000 - 13000	-	30
13000 - 16000	-	90
33000 - 40000	-	4

Table 3. ELECTROMAGNETIC ENVIRONMENTAL LEVELS OF MIL-STD-1385B, 1 AUG 1986: [Ref. 15]

Frequency (MHz)	Field Intensity [V(rms)/m]	Average Power Density (mW/cm^2)
Communications		
0.2 - 0.6	300	-
0.6 - 1.5	200	-
1.5 - 32.0	200	-
32.0 - 100.0	-	1
100.0 - 200.0	-	1
200.0 - 790.0	-	1
Radars/Other Electronic Equipment		
150 - 225	-	20
225 - 790	-	15
790 - 850	-	100
850 - 950	-	100
950 - 1400	-	100
1400 - 2700	-	100
2700 - 3600	-	400
3600 - 5400	-	100
5400 - 5900	-	400
5900 - 7900	-	100
7900 - 8400	-	175
8400 - 8500	-	400
8500 - 11000	-	400
11000 - 14000	-	100
14000 - 18000	-	100
33000 - 40000	-	4

APPENDIX F. HERO WEAPON EVALUATION TEST PROCEDURES

As noted in APPENDIX D, HERO weapon evaluation tests aboard ships and field activities begun in 1966. The following is an outline of the major steps in such an evaluation:

- Request Time, 13 weeks prior to test.
- Weapons Officer provides appropriate documentation 12 weeks prior to test.
- Weapons Officer provides a complete inert weapon and 12 of each EED in that weapon 10 weeks prior to the test.
- Consultation with field and command personnel 9 weeks prior to the test.
- Review and Submission of the test plan 8 weeks prior to the test.
- Approval of the test plan 6 weeks prior to the test.
- Special equipment installed into the weapons 4 weeks prior to the test.
- Perform test over a 2 week period leading to week 0.
- Prepare test report at week 0.
- Review of test report.
- Certify weapons if the test is satisfactory.

APPENDIX G. SUSCEPTIBILITY CURVES

The following graphs are a series of susceptibility curves for communication and radar frequencies. These graphs give the amount of power density (for radar frequencies) or electric field strength (for communication frequencies) necessary to present a potential hazard to ordnance. Figure 1 and Figure 3 on page 80 are curves for communication frequencies and Figure 2 on page 79 and Figure 4 on page 81 are curves for radar frequencies. Figure 1 and Figure 2 on page 79 represent field intensities that are potentially Hazardous to ordnance in optimal coupling configurations while Figure 3 on page 80 and Figure 4 on page 81 represent field intensities that are potentially hazardous to susceptible weapons which require special restrictions. [Ref. 15]

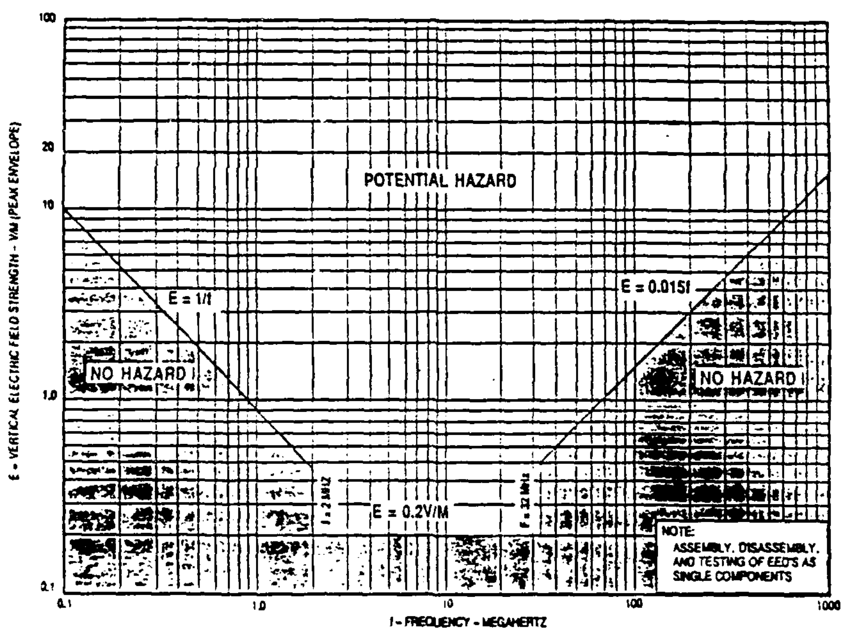


Figure 1. Optimum Coupling Configuration - Communication frequencies

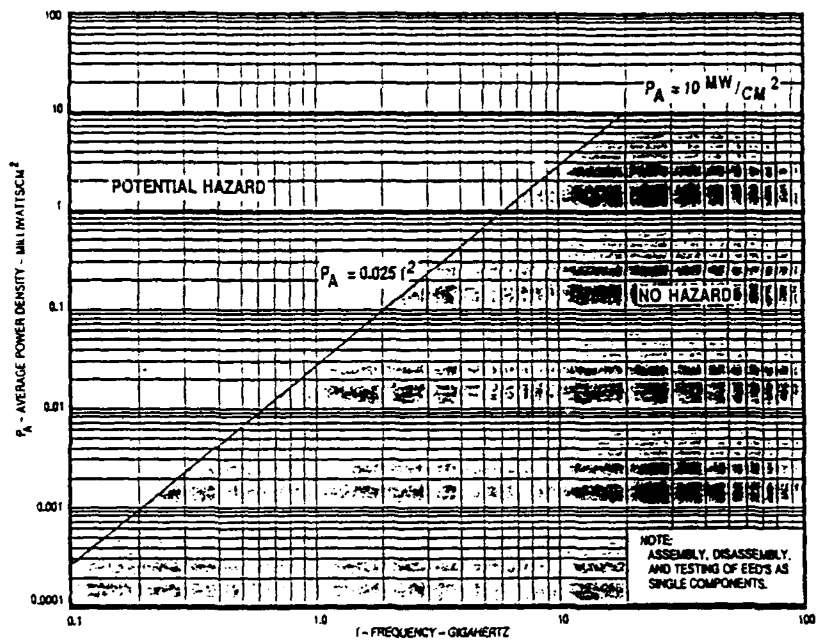


Figure 2. Optimum Coupling Configuration - Radar frequencies

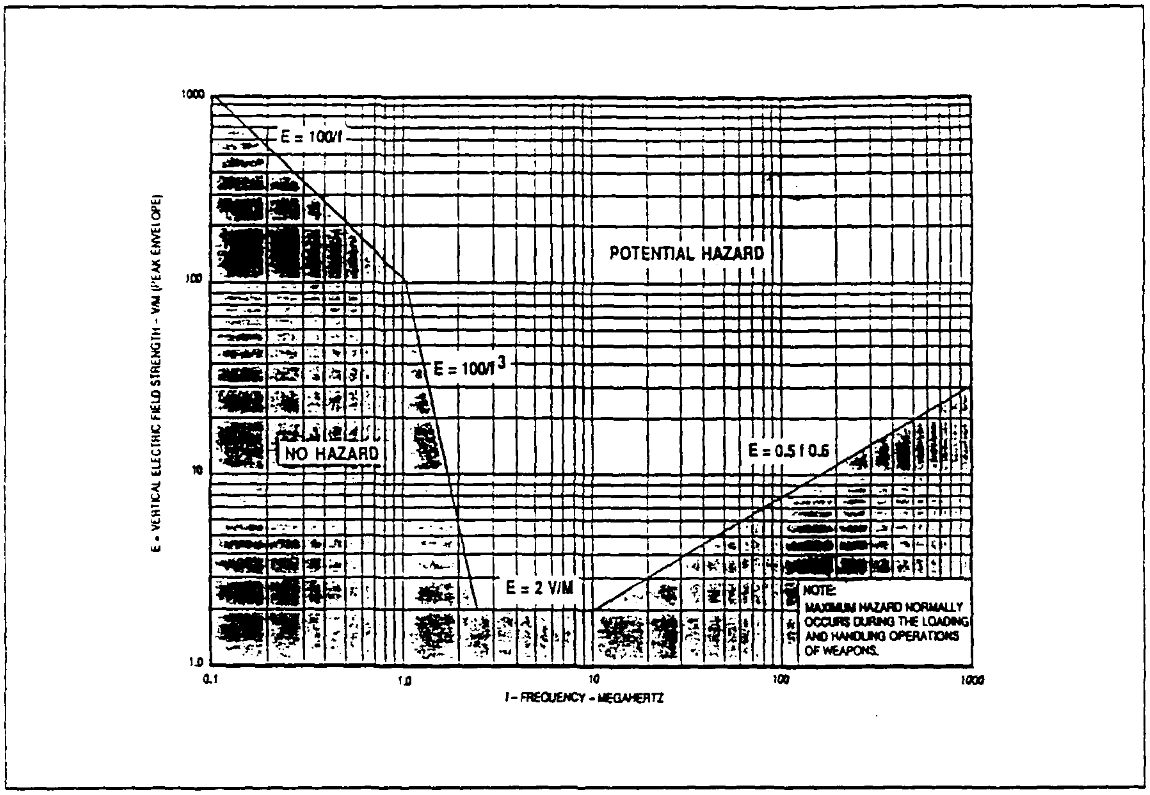


Figure 3. Weapons Requiring Restrictions - Communication frequencies

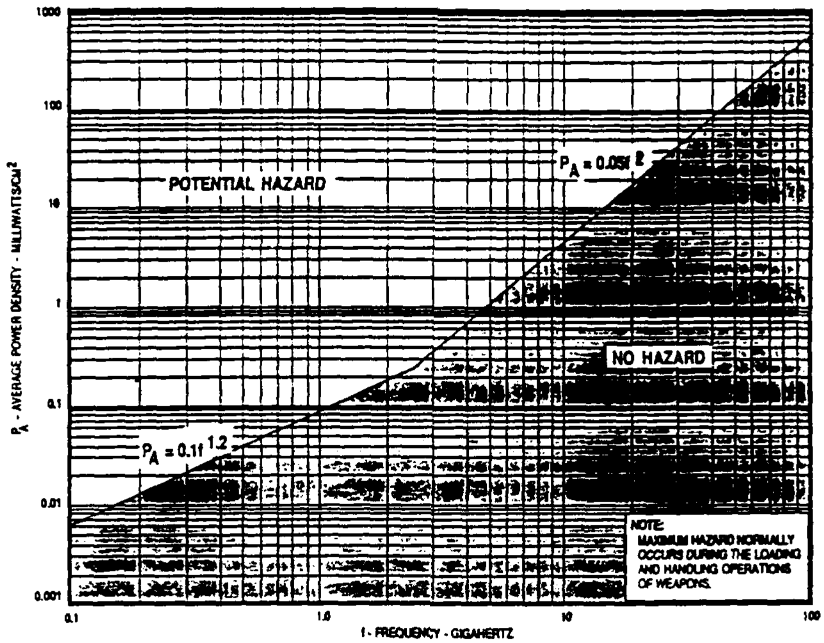


Figure 4. Weapons Requiring Restrictions - Radar frequencies

APPENDIX H. TABLES

Table 4. TYPICAL COLLECTORS OF EMP ENERGY: [Ref. 1 : p. 520]

*Long runs of cable, piping, or conduit
*Large antennas, antenna feed cables, guy wires, antenna support towers
*Overhead power and telephone lines and support towers
*Long runs of electrical wiring, conduit, etc., in buildings
*Metallic structural components (girders), reinforced bars, corrugated roof, expanded metal lath, metallic fencing
*Railroad tracks
*Aluminum aircraft bodies

Table 5. DEGREES OF SUSCEPTIBILITY TO THE EMP: [Ref. 1 : p. 525]

Most Susceptible	
Low-power, high-speed digital computer, either transistorized or vacuum tube (operational upset)	
Systems employing transistors or semiconductor rectifiers (either silicon or selenium):	
Computers and power supplies	
Semiconductor components terminating long cable runs	
Alarm systems	
Intercom system	
Life-support system controls	
Some telephone equipment that is partially transistorized	
Transistorized receivers and transmitters	
Transistorized 60 to 400 cps converters	
Transistorized process control systems	
Power system controls and communication links	
Less Susceptible	
Vacuum-tube equipment that does not include semiconductor rectifiers:	
Transmitters	Intercom systems
Receivers	Teletype-telephone
Alarm systems	Power Supplies
Equipment employing low-current switches, relays, meters:	
Alarms	Panel indicators and status boards
Life-support systems	
Power system control panels	Process controls
Hazardous equipment containing:	
Detonators	Explosive mixtures
Squibs	Rocket fuels
Pyrotechnical devices	
Other:	
Long power cable runs employing dielectric insulation	
Equipment associated with high-energy storage capacitors	
Inductors	
Least Susceptible	
High-voltage 60 cps equipment:	
Transformers, motors	Rotary converters
Lamps(filament)	Heavy-duty relays,
Heaters	Circuit breakers
Air-insulated power cable runs	

Table 6. ELECTRONIC COMPONENTS IN DECREASING SENSITIVITY: [Ref. 1 : p. 524]

Microwave semiconductor diodes(most sensitive)
Field-effect transistor
Silicon-controlled rectifiers
Audio transistors
Power rectifier semiconductor diodes
Vacuum tubes(least sensitive)

Table 7. ATTRIBUTES INVOLVING HARDENING DESIGN: [Ref. 5 : p. 89]

GOOD ATTRIBUTES	BAD ATTRIBUTES
EMP Attenuation	Weight
Reliability	Initial Cost
Maintainability	Verification Costs
Life	Hardness Surveillance Costs
Ease of Testing	Maintenance Costs

Table 8. **THE BENEFITS OF SHIELDING:** [Ref. 5 : p. 90]

Feature	Benefit(s)
*Can attenuate "Wartime" EMP signals down to level of "Peacetime" system noise	*Can be certain system will survive and if it works in peacetime it will work in wartime *Do not need to test electronic susceptibility to verify hardness *Do not need to control parts
*Can test shielding effectiveness rather quickly and easily -techniques exist to find leaks -can use commercial equipment	*Hardness assessment relatively simple *Hardness surveillance relatively simple *Hardness maintenance relatively simple *Minimum downtime for assessment, surveillance, and maintenance *Lower life cycle cost
*Can provide protection for all equipment inside shield	*Allows future modifications to be made easily without impacting EMP hardness

Table 9. **WORST RF ENVIRONMENTAL CONDITIONS:** [Ref. 15]

Frequency	Power	Power expected in the Future
.150 - 2 Mc	8000 watts	
2 - 26 Mc	10000 watts	
27 - 55 Mc	4 watts	
115 - 160 Mc	120 watts	
215 - 225 Mc	1500000 watts	5000000 watts
225 - 400 Mc	750 watts	
960 - 3000 Mc	500000 watts	25000000 watts
3000 - 10025 Mc	2000000 watts	10000000 watts

Table 10. RF ENVIRONMENT CRITERIA TO BE APPLIED IN WEAPONS DESIGNS: [Ref. 38]

Frequency (Mc)	Distance from Antenna (ft)	Field Intensity		
		Electric Field (V/M)	Magnetic Field (amp/M)	Power Density (mW/cm^2)
Communications Equipment				
0.25 - .535	10	300	0.5	-
2 - 32	10	100	0.5	-
100 - 156	100	-	-	0.01
225 - 400	100	-	-	0.01
Radar Equipment				
200 - 225				10
400 - 450	Fields	-	-	1
1000 - 1300	Measured	-	-	1
2700 - 3600	at Weapon	-	-	10
5400 - 5900	Locations	-	-	100
8500 - 10300				100
NOTE- The above values do not reflect incorporation of AN SPG-59 radar.				

Table 11. SUMMARY OF SENSOR CHARACTERISTICS: [Ref. 15]

Sensor	Quantity Detected	Sensitivity	Time Response	Perturbation of Bridgewire Thermal Characteristics	Perturbation of Bridgewire RF Characteristics	Frequency Selective
Radiation Thermocouple Vacuum Deposited	Temperature	Good	Medium	Negligible	Negligible	No
Radiation Thermocouple Wire	Temperature	Fair	Slow	Negligible	Negligible	No
Wire Thermocouple Attached to Bridgewire	Temperature	Excellent	Follows Bridgewire	Very Large	Large	No
Radiation Thermistor	Temperature	Good	Slow	Negligible	Negligible	No
Thermistor Attached to Bridgewire	Temperature	Excellent	Follows Bridgewire	Very Large	Large	No
Photoconductor (Uncooled)	Infrared EM Radiation	Poor	Very Fast	Small to Medium	Small	No
Photoconductor (Cooled)	Infrared EM Radiation	Excellent	Fast	Small to Medium	Small	No
Toroidal Coil	Electric Current	Excellent	Essentially Instantaneous	None	Small	Yes
Hall Effect Power Flow Probe	Electric Power Flow (Poynting Vector)	-	Essentially Instantaneous	None	-	No
Electron Emission Detector	Temperature	-	-	Small	None	No
Photo EM Detector (PEM)	Infrared EM Radiation	Very Poor	Very Fast	-	Small	No

Table 12. SUMMARY OF SENSOR CHARACTERISTICS (CONTINUED)

Sensor	Reliability	Ease of Fabrication	Relative Cost to Make Large Quantities of Sensors	Susceptibility of Instrumentation to RF	Adaptability to Automatic Data Recording	Other Complications
Radiation Thermocouple Vacuum Deposited	Good	Good	Low	None from dc to 1 kMc	Excellent	-
Radiation Thermocouple Wire	Excellent	Good	Low	None from dc to 1 kMc	Excellent	Require low level dc Amplifiers
Wire Thermocouple Attached to Bridgewire	Good	Poor	-	None from dc to 500 Mc	Excellent	-
Radiation Thermistor	Excellent	Fair	Medium	None from dc to above 1 kMc	Fair	Require Bridge Balancing
Thermistor Attached to Bridgewire	Excellent	Fair	Medium	None from dc to 500 Mc	Fair	-
Photoconductor (Uncooled)	-	Poor	Very High	-	Fair	Requires Radiation Chopper
Photoconductor (Cooled)	-	Poor	Excessive	-	Fair	Requires Radiation Chopper and Cooling
Toroidal Coil	Excellent	Poor	Medium	Unusable above 100 Mc	Poor	Requires Tuning
Hall Effect Power Flow Probe	-	-	-	None	-	Requires low Level dc Amplifiers
Electron Emission Detector	-	-	-	None	Excellent	Requires Magnetic Field and Constant Source
Photo Electromagnetic Detector (PEM)	-	Poor	Very High	-	Fair	Same as above

Table 13. **GROUND PLANE TRANSMITTERS:** 1962-1970 [Ref. 15]

Year Obtained	Transmitter	Frequency	Power
Before 1960	AN FRT-5	4-26 MHz	15 kW avg., 1 in 1962, 2 more 1964 5
1966	TAB-7	Replaced T-171	-
1966	APS-20	2.88 GHz	2 MW
1966	SPS-17	215-225 MHz	1.8 kW avg., 300 kW peak
1966	Franklin Institute, A, B, and c Bands	350 MHz-1GHz	250 kW avg.
1970	SCR 584 MODIFIED	1-10 GHz	200 kW peak, replaced all radars

Table 14. **GROUND PLANE TRANSMITTERS:** 1972-1982 [Ref. 15]

Year Obtained	Transmitter Band	Frequency	Power
1972	AN FRT-85	2-30 MHz	20 Kw avg., 40 kW peak
1973	Saunders Modulator	2-35 GHz	1 mW (Magnetron)
1972	"MCL"	50-1000 MHz	1 kW avg.
1975	Sanders A	140-240 MHz	2 kW avg., 300 kW peak
1975	Sanders B	590-480 MHz	replaced SPS-17
1979	Sanders A	140-240 MHz	2 kW avg., 300 kW peak
1979	Sanders B	590-480 MHz	300 kW peak
1979	Sanders C	870-960 MHz	2 kW avg., 250 kW peak
1982	Sanders C	870-960 MHz	2 kW avg., 250 kW peak

Table 15. **ESTIMATE ENERGY REQUIRED FOR EMP FAILURE:** [Ref. 3 : p. 430]

Device Type	Failure Energy (μ joules)
Point-contact diodes 1N82A-1N69A	0.7 - 12
Integrated circuits μA709	10
Low-power transistors 2N930-2N1116A	20 -1000
High-power transistors 2N1039(Ge)	1000
Switching diodes 1N914-1N933J	70 -100
Zener diodes 1N702A	1000
Rectifiers 1N537	500
Relays (welded contacts)	2-100 x 10^3
Resistors (0.25 W carbon)	10^4

Table 16. **SEMICONDUCTOR JUNCTION DEVICE EMP DAMAGE CONSTANT GUIDELINES:** [Ref. 3 : p. 433]

Type of Semiconductor	Damage Constant K ($W(s)^{0.5}/cm^2$)		
	Range Minimum	Range Maximum	Recommended Damage Constant Limit
Diodes			
Rectifier	5 x 10^{-1}	2 x 10^{1}	> 3 x $10^{[illegible]}$
Reference	1 x 10^{-1}	1 x 10^{1}	> 1 x $10^{[illegible]}$
Switching	1 x 10^{-2}	1 x 10^{0}	> 1 x 10^{-1}
Point Contact	5 x 10^{-4}	1 x 10^{-1}	> 1 x 10^{-2}
Microwave	3 x 10^{-4}	3 x 10^{-2}	> 3 x 10^{-3}
Transistors			
High Power	2 x $10^{[illegible]}$	5 x $10^{[illegible]}$	> 1 x 10
SCR	2 x 10^{-1}	1 x $10^{[illegible]}$	> 1 x 10
Germanium	2 x 10^{-2}	1 x $10^{[illegible]}$	> 2 x 10^{-1}
Switching	2 x 10^{-2}	3 x 10^{-1}	> 1 x $10^{[illegible]}$
Low Power	8 x 10^{-3}	2 x $10^{[illegible]}$	> 1 x $10^{[illegible]}$
Integrated Circuits			
Input signal-to-ground	3 x 10^{-4}	2 x 10^{-1}	> 1 x 10^{-2}

Table 17. **CHARACTERISTIC OF SHIELD MATERIALS:** [Ref. 17 : p. 40]

Name of Material	Remarks (High Permeability Materials)	Resist. (ohm-cm x 10^{-6}) at 20°C	Relative Conduct. Referred to Cooper (σ)	Initial Permeab. Relative to Free Space (μ)	$\sigma\mu$	$\frac{\sigma}{\mu}$
Iron, Purified	99.95% Fe Heat Treatment 1480° C (H_2) + 88:f.0° C	10	.17	5000	8.5 x 10^2	3.4 x 10^{-5}
78 Permalloy	78.5% Ni, 21.2% Fe, 0.3% Mn Heat Treatment 1050° C + 600° quenched	16	.11	8000	8.8 x 10^2	1.4 x 10^{-5}
45 Permalloy	45% Ni, 54.7% Fe, 0.3% Mn Heat Treatment 1050° C	45	.038	2500	9.5 x 10^1	1.5 x 10^{-5}
Hipernik	50% Ni, 50% Fe Heat Treatment 120 0° C (H_2)	50	.034	4500	1.5 x 10^2	7.5 x 10^{-4}
4-79 Permalloy	79% Ni, 16.7% Fe, 4% Mo, 0.3% Mn Heat Treatment 1100° C + quenched	55	.031	20000	6.2 x 10^2	1.5 x 10^{-6}
Hymu 80	80% Ni, Bal. Iron	58	.030	10000	3.0 x 10^2	3.0 x 10^{-4}
Supermalloy	79% Ni, 15.7% Fe, 5% Mo, 0.3% Mn Heat Treatment 1300° C (h_2) + quenched	60	.029	100000	2.9 x 10^3	2.9 x 10^{-7}
Iron, 4% Silicon	96% Fe, 4% Si, Heat Treatment 80 0° C Anneal quenched	60	.029	500	1.4 x 10^1	5.8 x 10^{-5}
Mu Metal	75% Ni, 18% Fe, 2% Cr, 5% Cu Heat Treatment 1175° C (H_2)	62	.028	20000	5.6 x 10^2	1.4 x 10^{-6}

Table 18. TYPICAL APPLICATIONS OF EEDS: [Ref. 17]

Rocket Ordnance
Ignition systems for solid and liquid propellant rockets Explosive actuation of battery systems Explosive mechanical detents Detonators for warheads
Guided Missiles
Ignition systems for solid and liquid propellants Explosive actuation of relays, switches, and valves Self-destruct systems Power for electric generators Power for gyroscopic guidance systems Power for control surfaces Separation of nose cones Inflation of flotation bags for recovery systems Detonation for warheads
Aircraft
Jettison of wing tanks, pods, and cargo Ejection of bombs, seats, rockets, and canopies Launching of aircraft Actuation of emergency hydraulic systems Starter units for jet engines Fuses for Bombs, rockets, and missiles Primers for gun ammunition
Shipboard
Primers for large gun ammunition Fuses and charges for mines, depth charges, and torpedoes

Table 19. COMPARISON OF SENSITIVITY OF THREE TYPES OF EEDS: (hypothetical Data) [Ref. 28 : pp. 2-4]

Sensitivity Parameters	Wire-Bridge	Deposited Bridge	Exploding Bridge Wire
Capacitor Size (μf)	4	0.01	1.0
Charging Voltage to Achieve 1% Firing Probability (volts)	27	70	600
Energy for 1% Firing Probability (ergs)	14,600	250	1,800,000
Constant Voltage for 1% Probability (volts)	1	10	N A
Constant Current for 1% Probability (milliamperes)	200	10	N A

Table 20. SAFE DISTANCE RESTRICTIONS FOR HERO UNSAFE ORDNANCE: [Ref. 28 : p. 3-5]

Frequency (MHz)	Transmitter Output in KW (AVERAGE)								
	< .005	.005-.1	.1-.3	.3-1	1-5	10	20	100	200
0.250 to 1	5 ft	250 ft	400 ft	750 ft	1600 ft	2300 ft	3200 ft	7150 ft	10000 ft
1 to 2	5 ft	450 ft	800 ft	1400 ft	3200 ft	4500 ft	6400 ft	14300 ft	20000 ft
2 to 32	5 ft	1100 ft	2000 ft	3600 ft	8000 ft	11300 ft	16000 ft	36000 ft	50000 ft
32 to 70	5 ft	470 ft	800 ft	1500 ft	3300 ft	4700 ft	6700 ft	15000 ft	26000 ft
70 to 100	5 ft	200 ft	350 ft	650 ft	1450 ft	2150 ft	2900 ft	6500 ft	9200 ft
100 to 200	5 ft	150 ft	260 ft	500 ft	1100 ft	1500 ft	2100 ft	4800 ft	6700 ft
200 to 400	5 ft	80 ft	130 ft	250 ft	540 ft	760 ft	1100 ft	2400 ft	3300 ft

Table 21. MINIMUM SUSCEPTIBILITY ENERGIES FOR VARIOUS CIRCUIT ELEMENTS: 1962-1970 [Ref. 34]

Item	Minimum Energy (Joules)	Malfunction
Logic circuit	2×10^{-9}	Circuit upset
Integrated circuit	4×10^{-10}	Circuit upset
Memory core	3×10^{-8}	Core erasure by wiring
Amplifier	4×10^{-21}	Interference (noise)
Relay	1×10^{-1} - 1×10^{-3}	Welded contacts
Microammeter	3×10^{-3}	Slammed meter
Transistors		
PNP audio	3×10^{-2}	burnout
NPN switching	1×10^{-3} - 1×10^{-5}	burnout
PNP switching	1×10^{-2} - 1×10^{-4}	burnout
Diodes	1×10^{-3} - 1×10^{-5}	burnout
SCR	3×10^{-3}	burnout
Vacuum tubes	1 - 2	burnout
Integrated circuit	8×10^{-6}	burnout

APPENDIX I. FIGURES

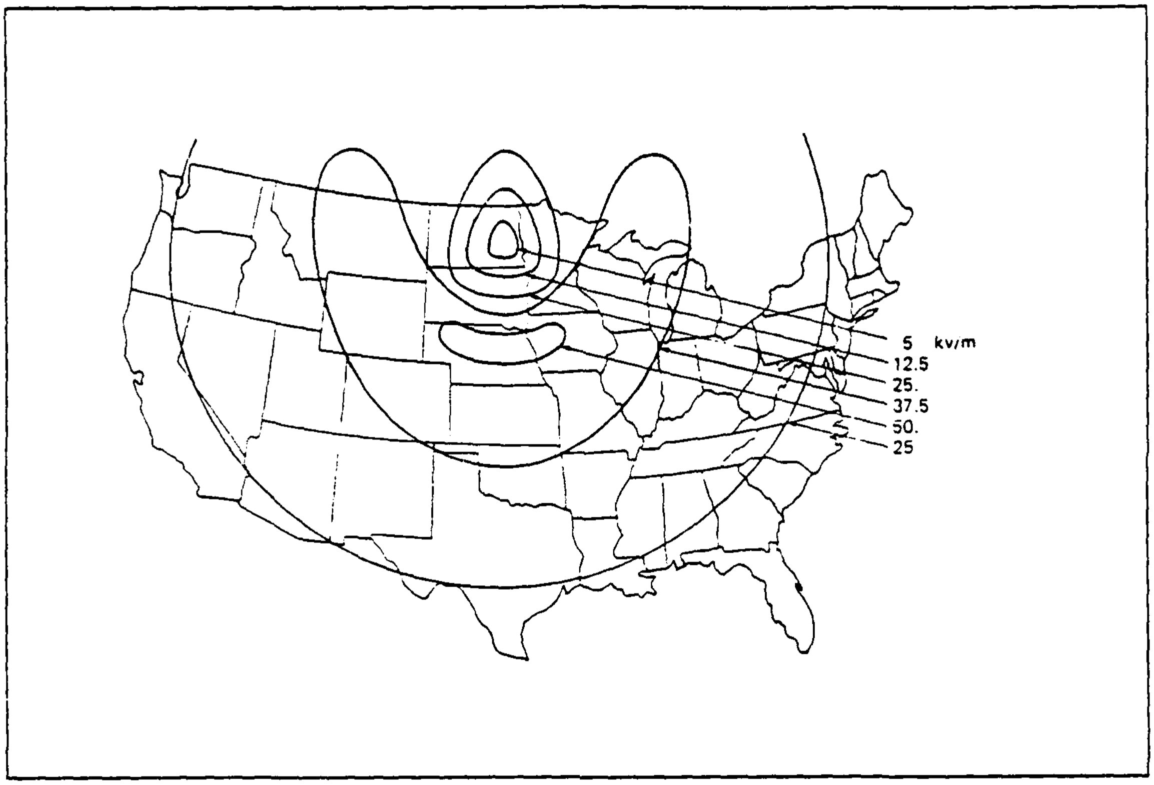


Figure 5. High Altitude EMP Electric Field Lines: Electric field contour at the earth's surface from a high altitude nuclear detonation. Corresponding magnetic field strengths can be up to 200 ampere turns per meter, which is 10 times that of the magnetic field of the earth at sea level. [Ref. 3: p. 327]

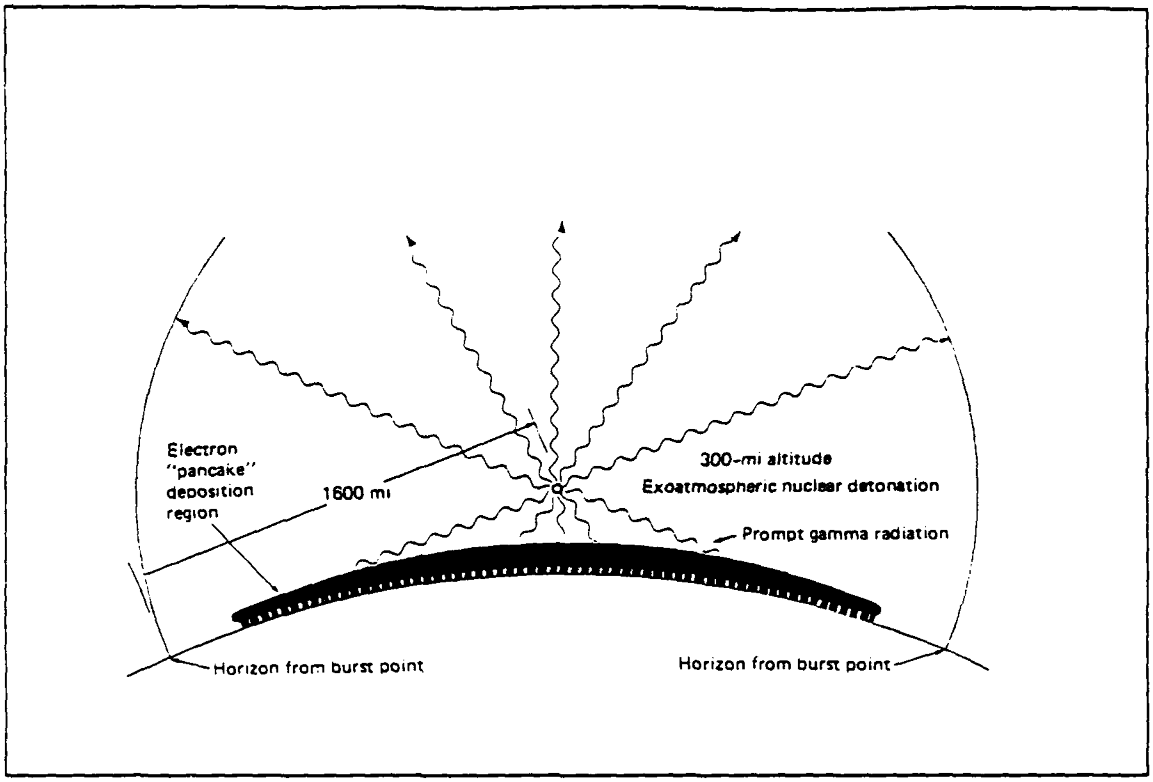


Figure 6. **High Altitude EMP:** EMP generated by a high-altitude detonation showing pancake deposition region produced by prompt gamma rays. [Ref. 3: p. 332]

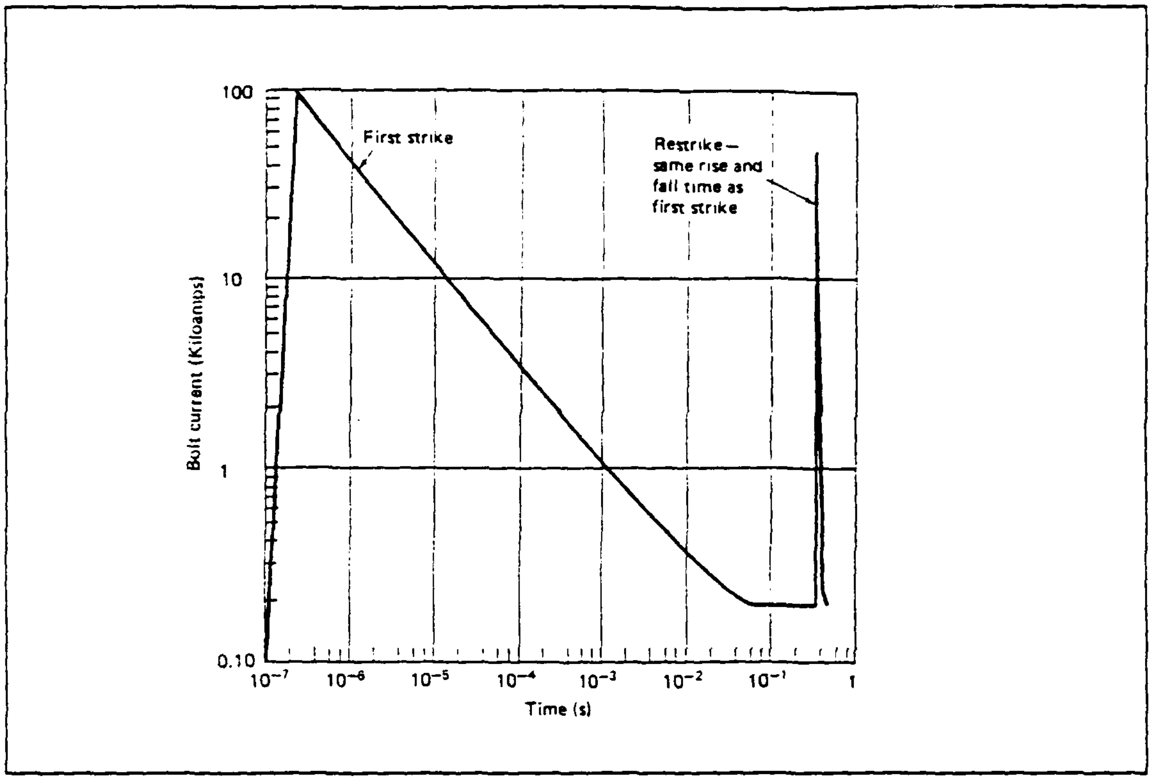


Figure 7. Lightning Waveform Showing First Strike and Restrike Phase: [Ref. 3: p. 32S]

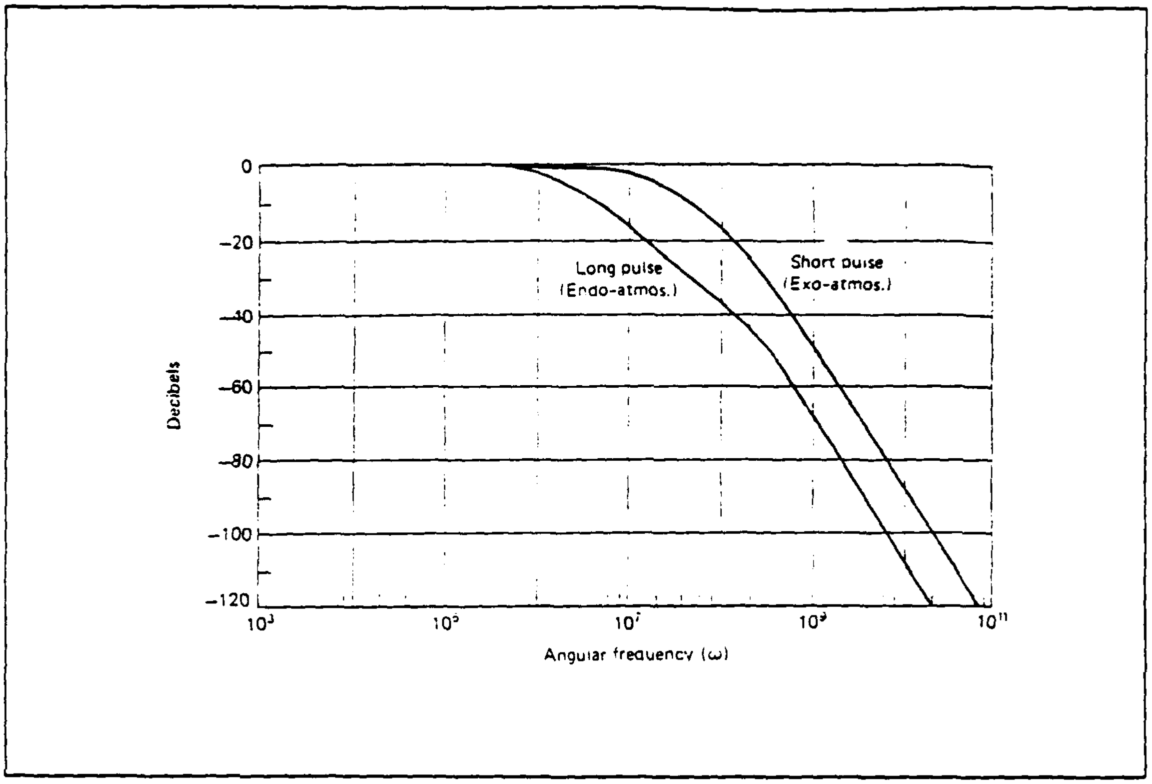


Figure 8. EMP Pulse Frequency Signatures: [Ref. 3: p. 330]

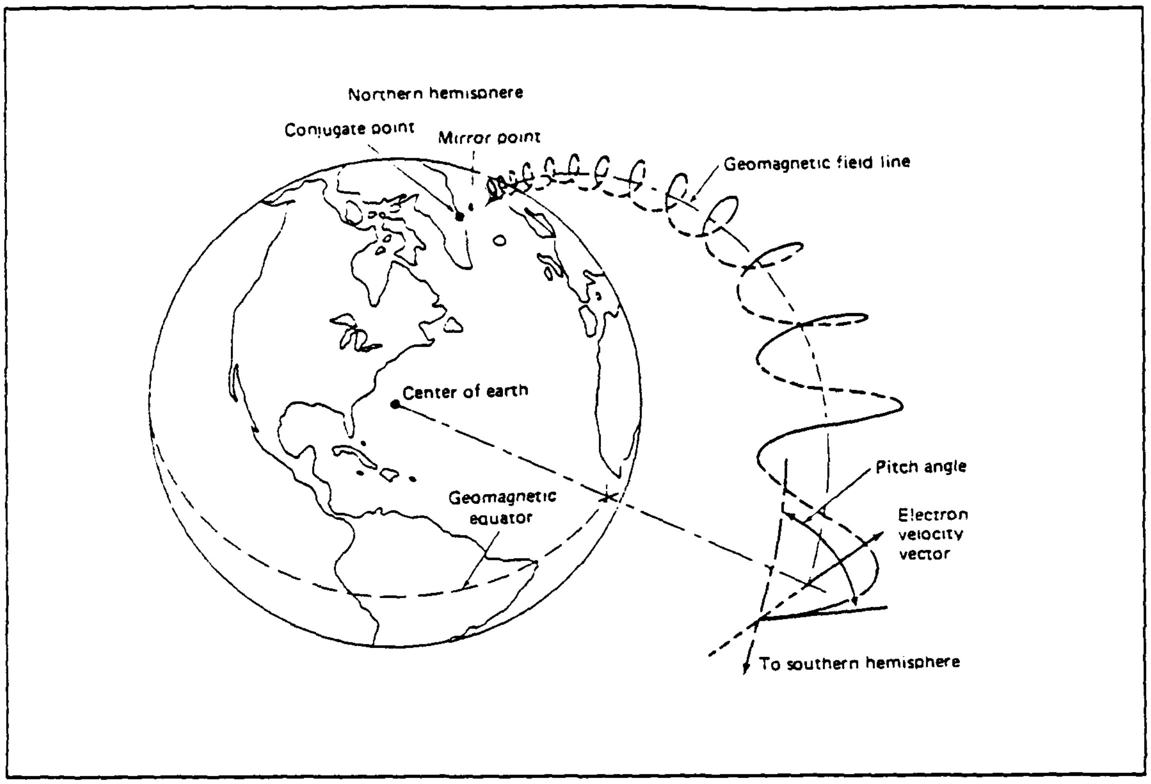


Figure 9. Trapped Argus Electron Motion in the Geomagnetic Field: [Ref. 3: p. 331]

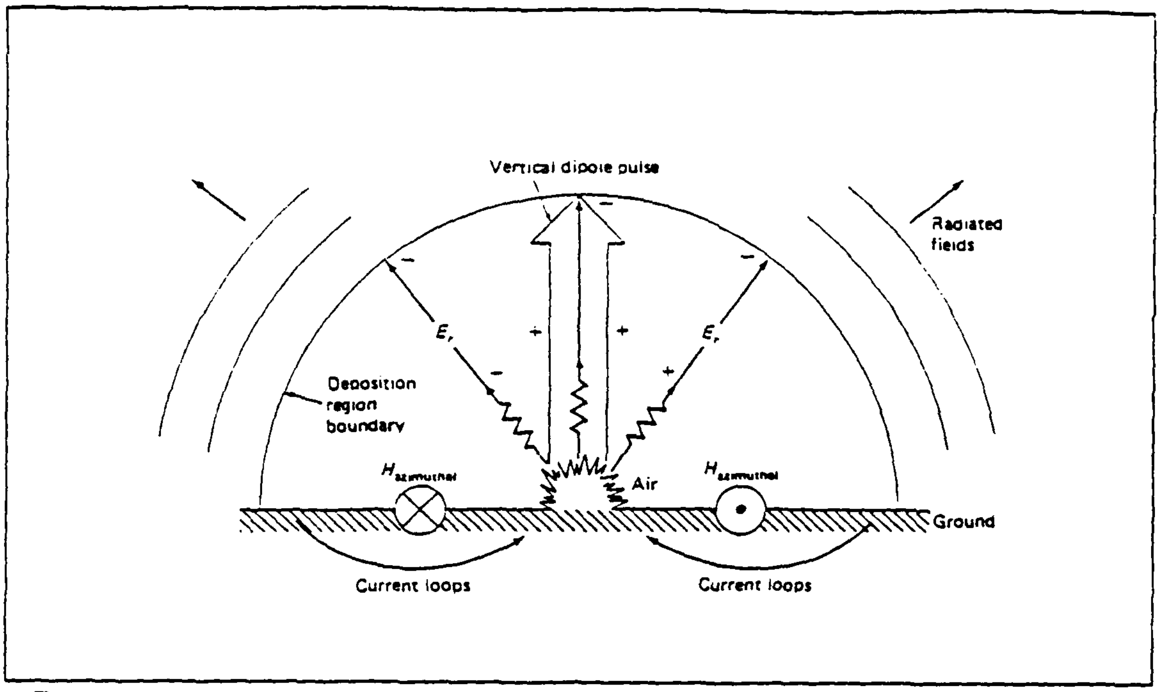


Figure 10. Surface Burst EMP: [Ref. 3: p. 334]

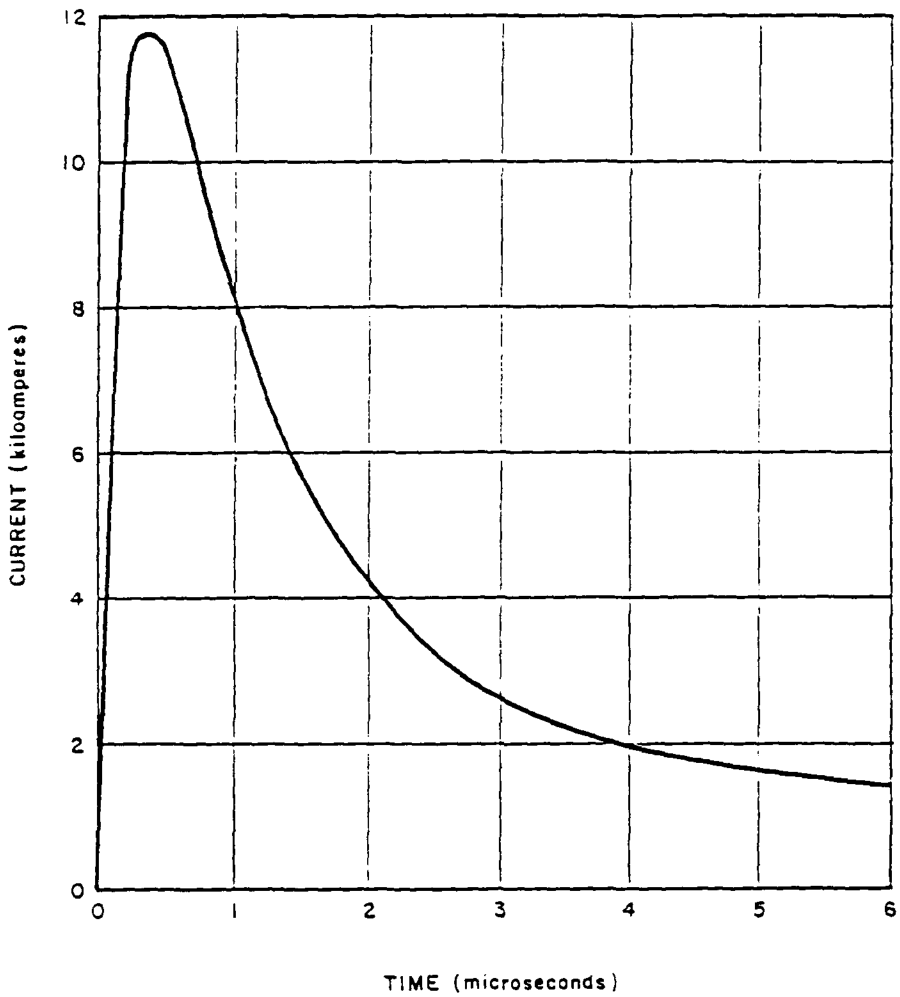


Figure 11. *Typical Form of the Current Pulse Induced by EMP:* [Ref. 1: p. 530]

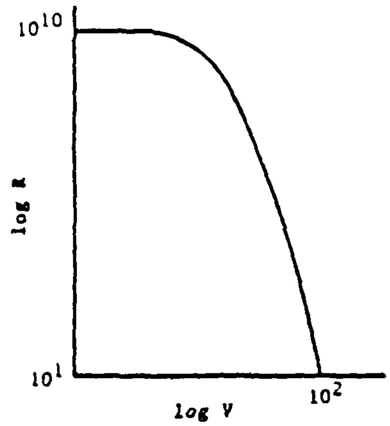


Figure 12. Resistance Versus Voltage of Voltage Variable Resistor: [Ref. 7: p. 153]

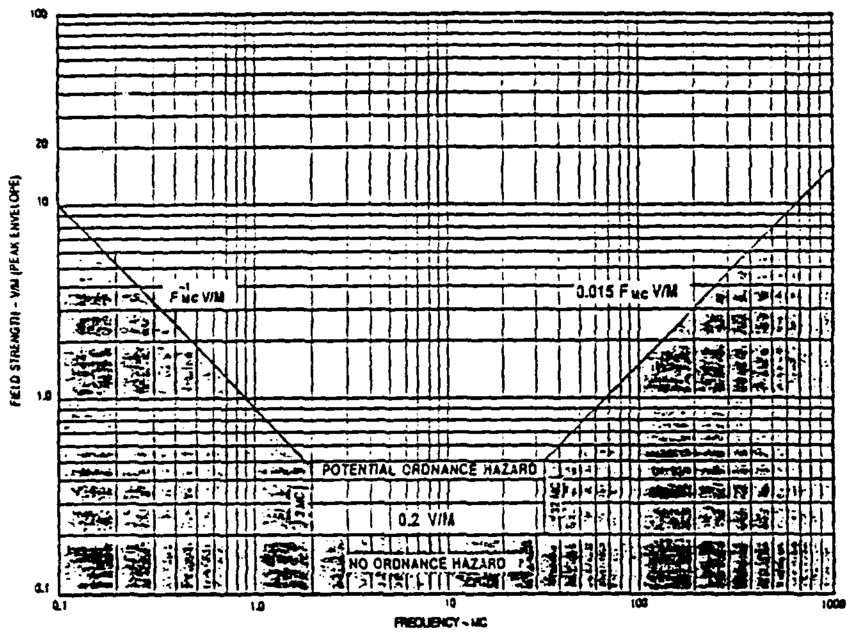


Figure 13. Hazardous Field Intensity to Ordnance - Radio Transmitters: [Ref. 15: p. 4-6]

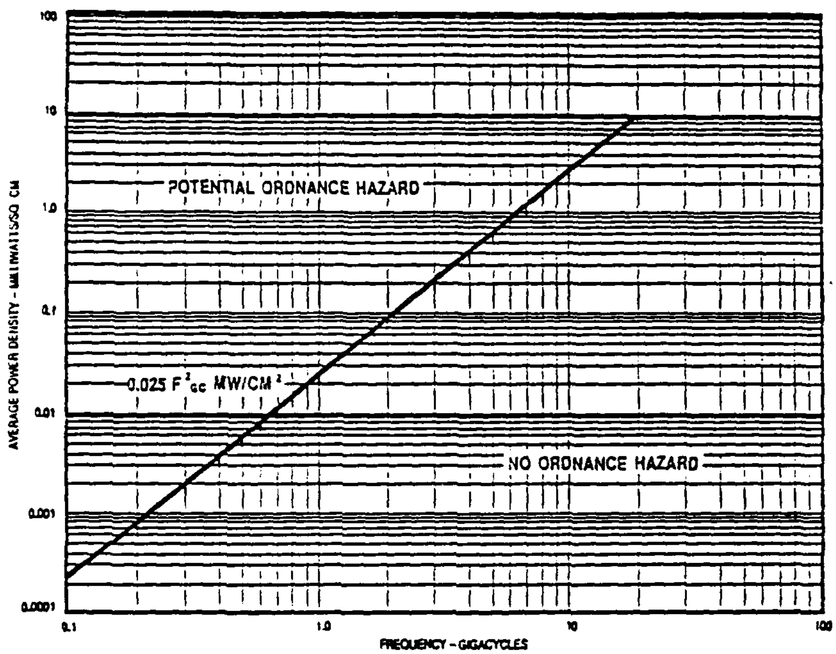


Figure 14. Hazardous Field Intensity to Ordnance - Radars: [Ref. 15: p. 4-7]

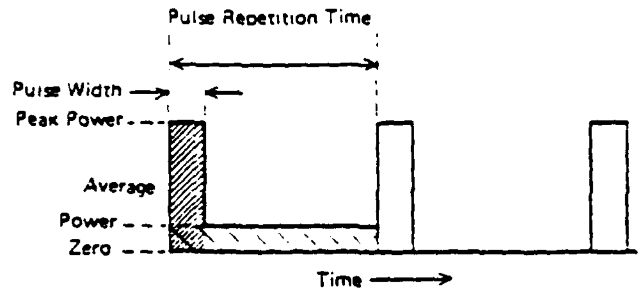


Figure 15. Pulse Transmission Relationships: [Ref. 17]

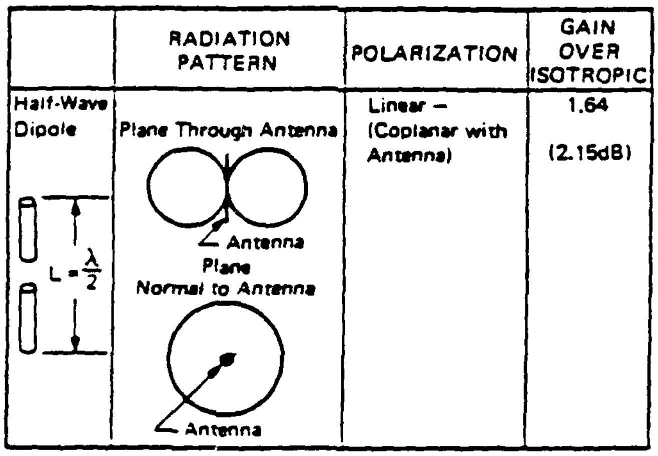


Figure 16. Characteristics of a Half-Wave Dipole: [Ref. 17]

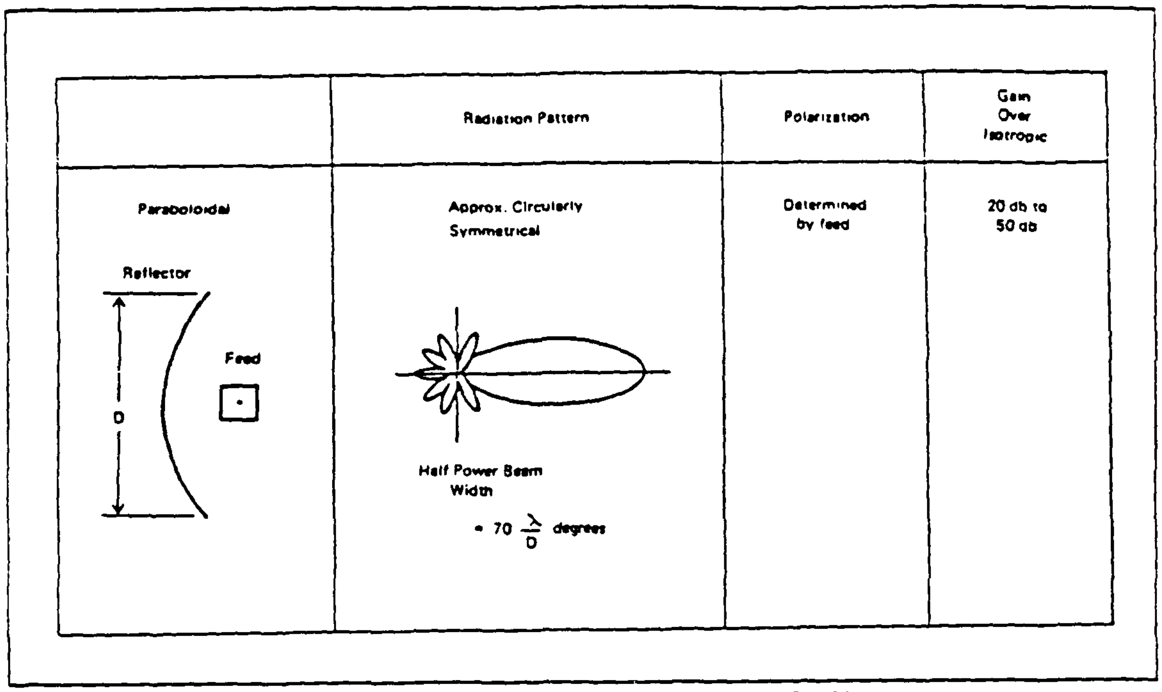


Figure 17. Characteristics of a Reflector Antenna: [Ref. 17]

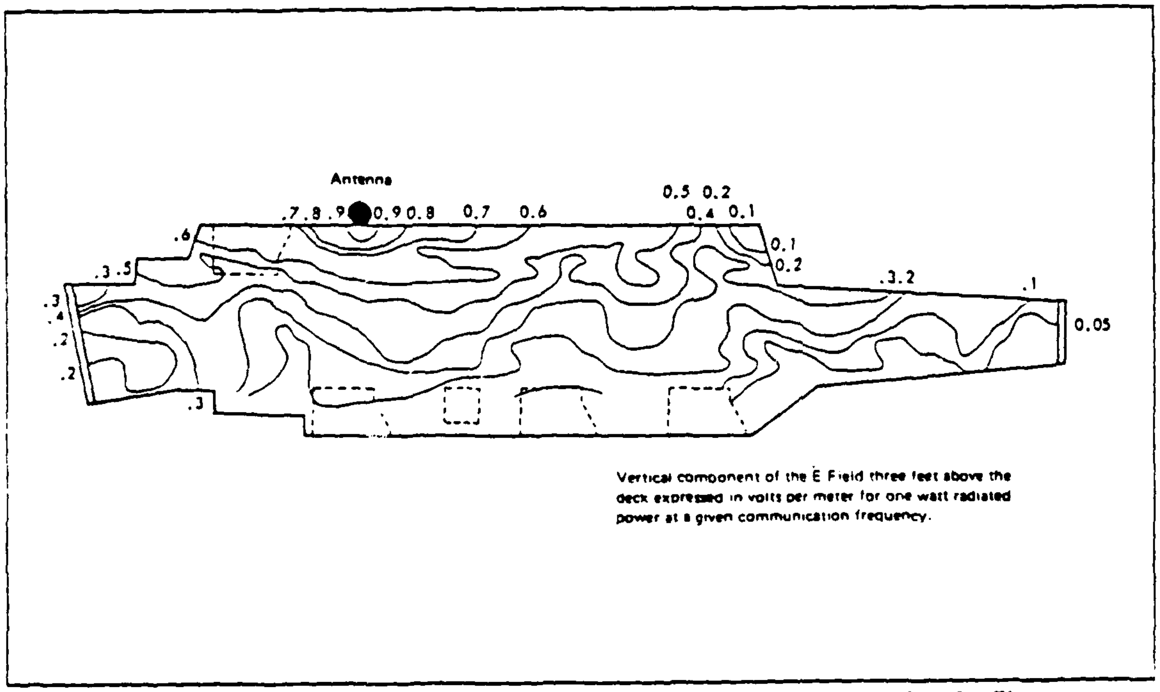


Figure 18. Typical Field Strength Contours on a Carrier Deck: [Ref. 17]

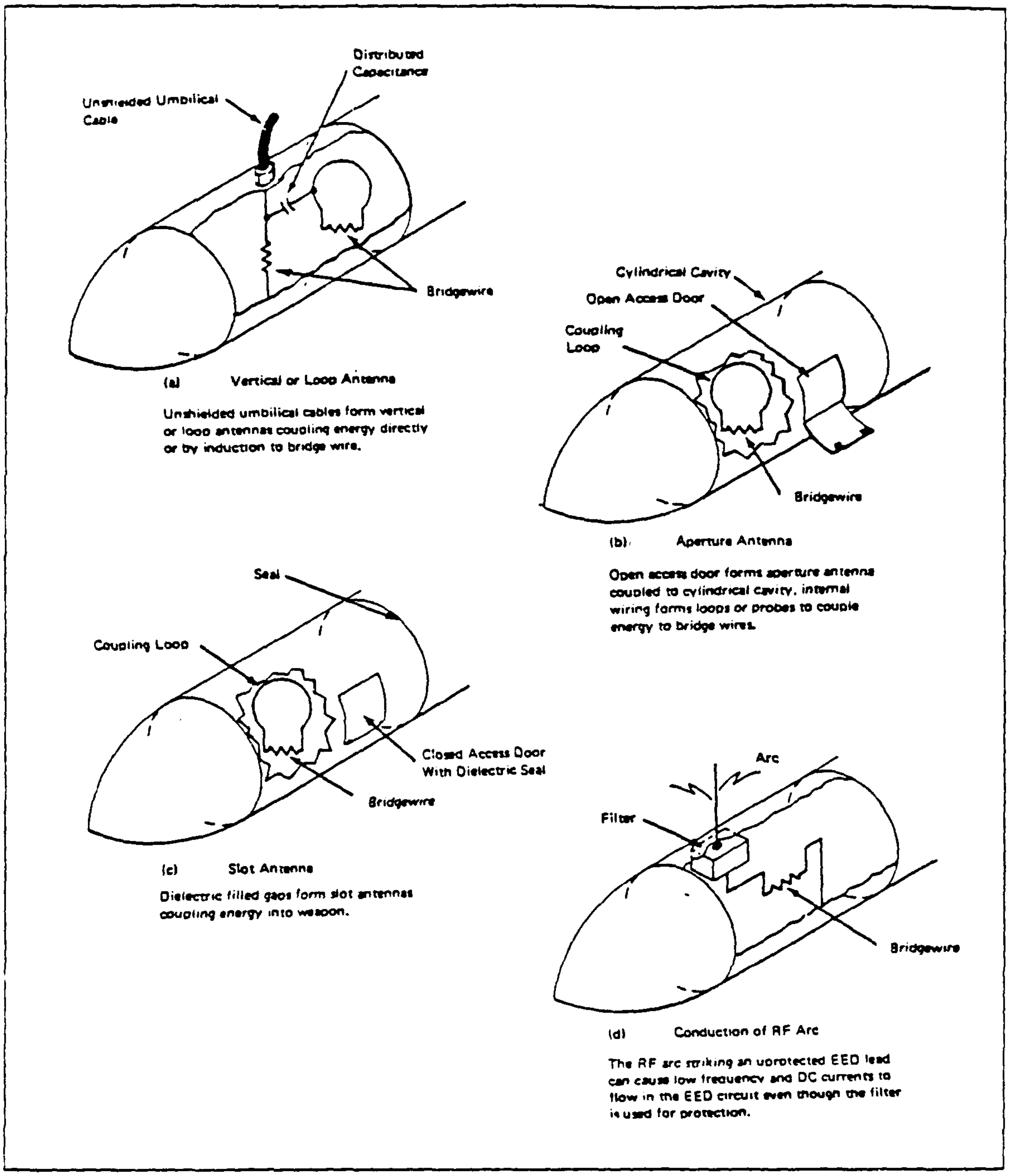


Figure 19. Ways Ordnance Components Function as Receiving Antennas: [Ref. 17]

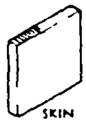
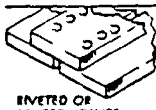
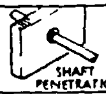
COMPONENT	EFFECT	HARDENING
 SKIN	DIRECT FIELD PENETRATION	METALLIC SKINS A MINIMUM OF THREE SKIN DEPTHS THICK: e.g., 10 MILS Al AND 40 MILS Ti @ 1 MHz. DIELECTRIC SKINS INSURE THAT NO CONTROL LINES LIE *DIRECTLY BENEATH SKIN.* WHERE POSSIBLE APPLY (CONTINUOUS OR STRIP) CONDUCTIVE COATING ($>10^7$ MHOS/M) OVER DIELECTRIC.
 RIVETED OR BOLTED JOINTS	SKIN CURRENT INDUCED VOLTAGE BUILD-UP AT JOINT, IF JOINT IMPEDANCE IS MUCH HIGHER THAN IMPEDANCE OF ADJOINING MATERIALS. THIS WOULD ALLOW EMP ENERGY TO COUPLE INTO STRUCTURE.	1. USE CLEAN AND SMOOTH BONDING SURFACES. 2. *AVOID SHARP CORNERS.* 3. UNIFORM PRESSURE ALONG JOINT (HIGH PRESSURE DESIRABLE). 4. CHEM FILMS.
 APERTURES	COUPLES ELECTROMAGNETIC FIELDS INTO STRUCTURE. H-FIELD PENETRATION PREDOMINATES NEAR CENTER OF STRUCTURE. E-FIELD PENETRATION DOMINATES AT ENDS OF STRUCTURE.	1. MINIMIZE NUMBER AND SIZE OF APERTURES. 2. WAVEGUIDE APPROACH (LENGTH: DIAMETER = 3 GIVES > 96 dB FOR EMP.) 3. WIRE MESH APPROACH (≥ 50% AREA COVERAGE AND 60 OR MORE STRANDS PER WAVELENGTH)
 SHAFT PENETRATIONS	SHAFT CONDUCTS EMP CURRENTS INTO STRUCTURE.	1. CIRCUMFERENTIALLY CONNECT FLEXIBLE CONDUCTOR (e.g., BRAID) TO SHAFT AND SKIN. 2. SHIELD CABLES NEAR SHAFT.

Figure 20. EMP Coupling into System: [Ref. 39: p. 65-10]

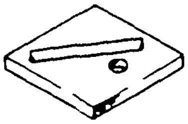
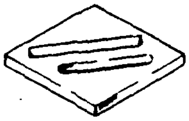
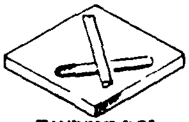
COMPONENT	EFFECT	HARDENING
 SMALL APERTURE	APERTURE FIELD EXCITATION OF CABLE.	1. ROUTE CABLE AROUND APERTURE IF PRACTICLE. 2. LOCATE CABLE NEAR GROUND PLANE (PROBABLY SKIN). a. E-FIELD APPROACHES ZERO NEAR GROUND PLANE. b. H-FIELD LOOP PICK-UP IS MINIMIZED.
 PARALLEL SLOT	SAME AS ABOVE	SAME AS ABOVE
 TRANSVERSE SLOT	SAME AS ABOVE	1. ROUTE CABLE AROUND APERTURE IF PRACTICAL. 2. SHIELD CABLE NEAR SLOT.

Figure 21. Cables Near Apertures: [Ref. 39: p. 65-10]

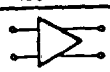
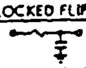
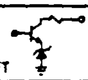
TECHNIQUE	COMMENT
 COMMON MODE REJECTION	EMP TRANSIENTS ON THE WIRES OF A CABLE ARE SIMILAR IN AMPLITUDE AND PHASE. A DIFFERENTIAL AMPLIFIER WILL, THUS, ONLY RESPOND TO THE DIFFERENCE IN THE EMP SIGNALS ON ITS SIGNAL AND RETURN LINES.
 BALANCING TRANSFORMER	THE BALANCING TRANSFORMER WILL CONVERT UNBALANCED SIGNALS TO BALANCED SIGNALS.
 CLOCK CLOCKED FLIP FLOP	THE PROBABILITY OF FLIP FLOP UPSET CAN BE REDUCED BY USING A CLOCKED FLIP FLOP WITH A CLOCK TIME GREATER THAN SEVERAL MICROSECONDS. UPSET CAN ONLY OCCUR DURING THE CLOCK TIME.
 LOW PASS FILTERS	LOW PASS FILTERS ATTENUATE THE HIGH FREQUENCY COMPONENT OF THE EMP CURRENT TRANSIENT. THE FILTERS SHOULD ABSORB RATHER THAN REFLECT THIS ENERGY.
 VOLTAGE LIMITATION	THE DIODES WILL LIMIT THE INPUT VOLTAGE. DIODES MAY HAVE TO BE SERIESED TO GET THE DESIRED INPUT VOLTAGE. ZENER DIODES AND SPARK GAPS MAY ALSO BE USED.
LOGIC LEVEL SHIFT 	THE ZENER DIODE WILL RAISE THE LOGIC THRESHOLD AND REDUCE THE NUMBER OF EMP TRANSIENTS WHICH WILL TRIGGER THE SWITCH:
LOGIC UPSET	CIRCUMVENTION

Figure 22. Circuit Hardening Against Transient Upset: [Ref. 39: p. 65-13]

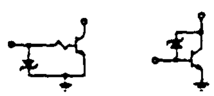
TECHNIQUE	COMMENT
DEVICE SELECTION	LARGE JUNCTION DEVICES REDUCE THE PROBABILITY OF JUNCTION BURNOUT. THESE DEVICES ARE, HOWEVER, INHERENTLY SOFT TO NEUTRONS. COMPROMISE REQUIRED.
 JUNCTION PROTECTION	CURRENT LIMITING RESISTORS (~10Ω) REDUCE JUNCTION POWER DISSIPATION. ZENER DIODES LIMIT THE BACK BIAS JUNCTION VOLTAGE. SPARK GAPS AND VARISTORS CAN ALSO BE USED FOR VOLTAGE LIMITING. THE DISADVANTAGES OF EACH OF THESE DEVICES MUST, HOWEVER, BE CONSIDERED BEFORE USAGE.
THIN FILM RESISTORS RT 26916	THIN FILM RESISTORS BECOME ELECTRICALLY OPEN UNDER VOLTAGE PULSING. WHERE POSSIBLE, THESE RESISTORS SHOULD NOT BE USED AT INTERFACES.

Figure 23. Circuit Hardening Against Permanent Damage: [Ref. 39: p. 65-13]

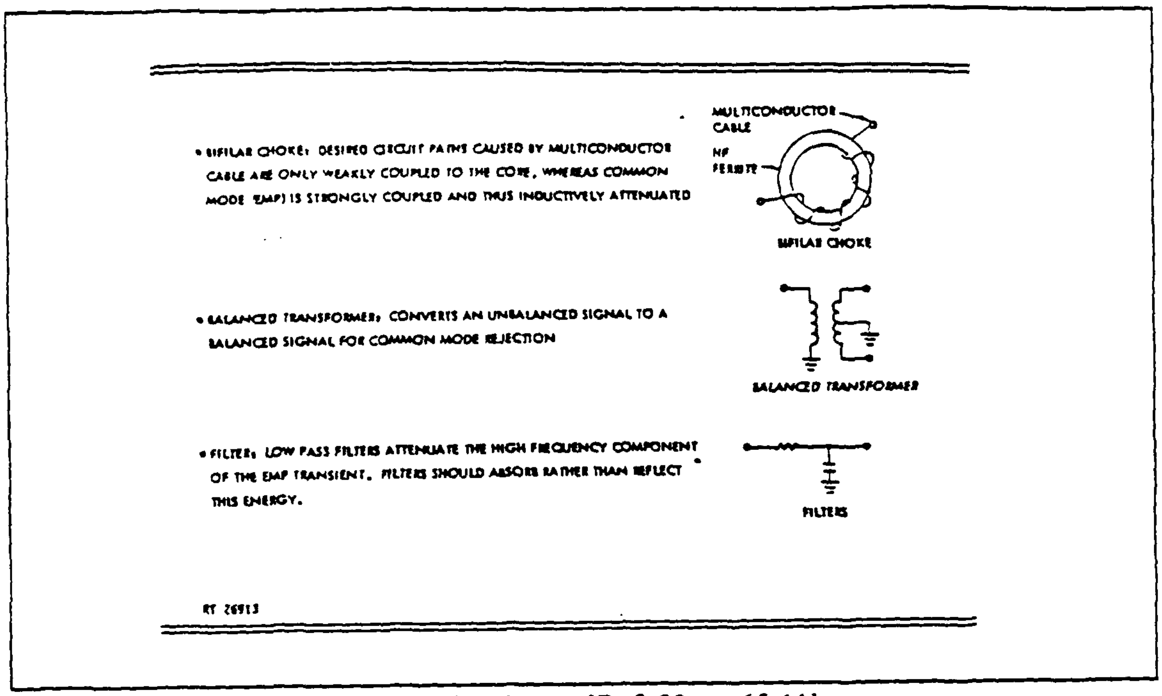


Figure 24. Passive Protective Devices: [Ref. 39: p. 65-11]

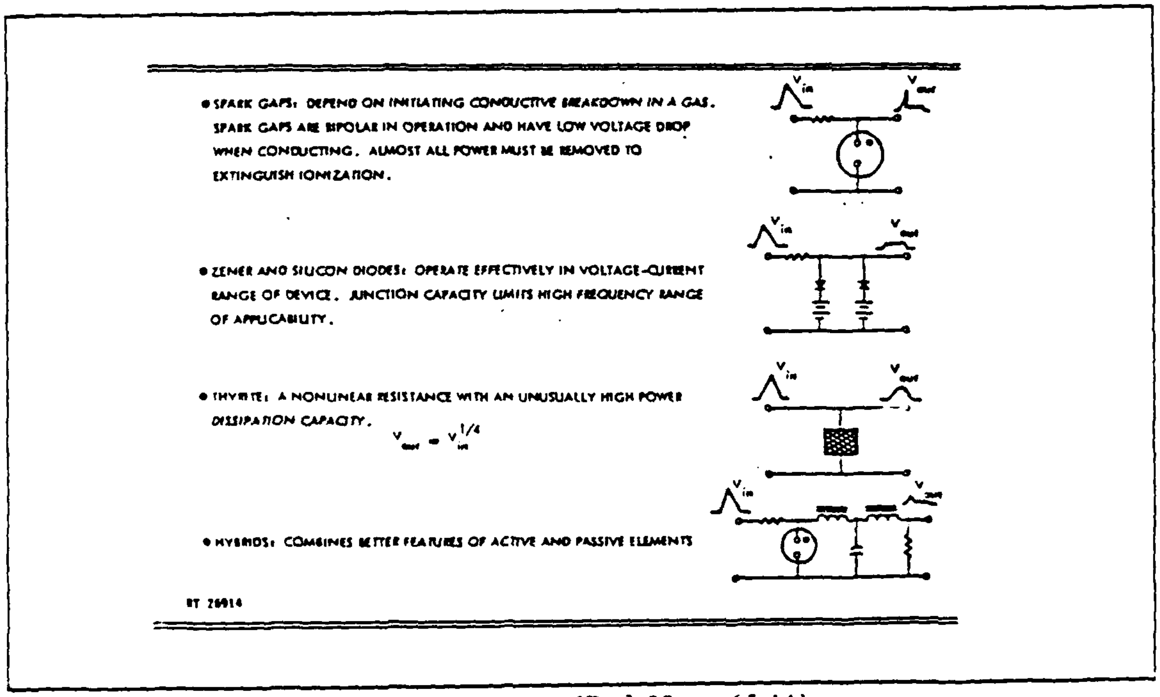


Figure 25. Active Protection Devices: [Ref. 39: p. 65-11]

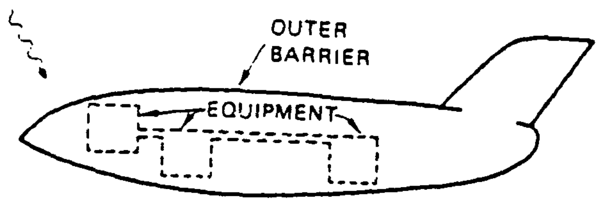


Figure 26. Allocation of Protection: [Ref. 6: p. 87]

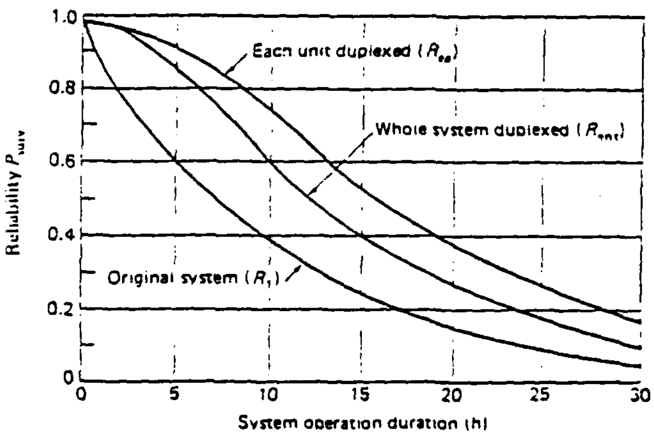


Figure 27. Reliability for High and Low Level Redundancy: [Ref. 3: p. 480]

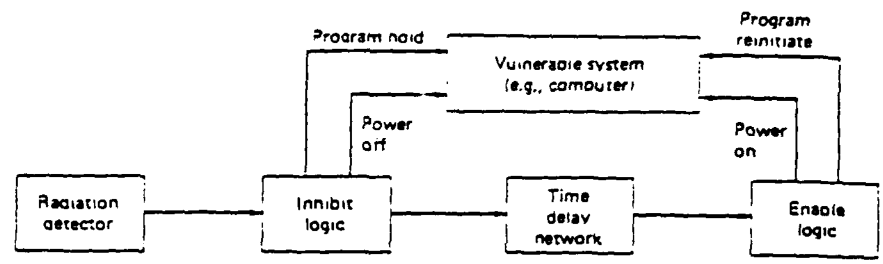


Figure 28. **Signal Flow Diagram of Circumvention System:** [Ref. 3: p. 482]

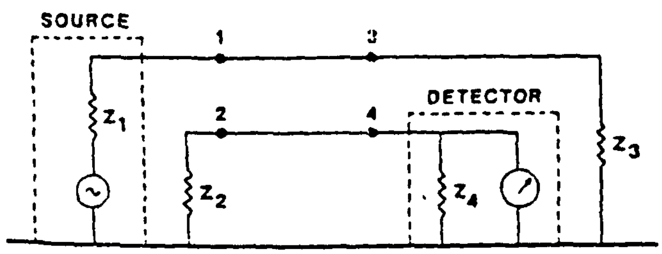


Figure 29. **A Typical Shielding Measurement:** The numbered circles represent points where connections can be made (ports). The upper solid line represents a drive circuit, with a signal source having an internal impedance Z_1 connected to port 1, and a load Z_2 connected to port 2. The dashed line represents a shield separating the drive and sense circuits. The bottom solid line represents a sense circuit, with a load Z_3 connected to port 3, and a detector with internal impedance Z_4 connected to port 4. [Ref. 26: p. 85]

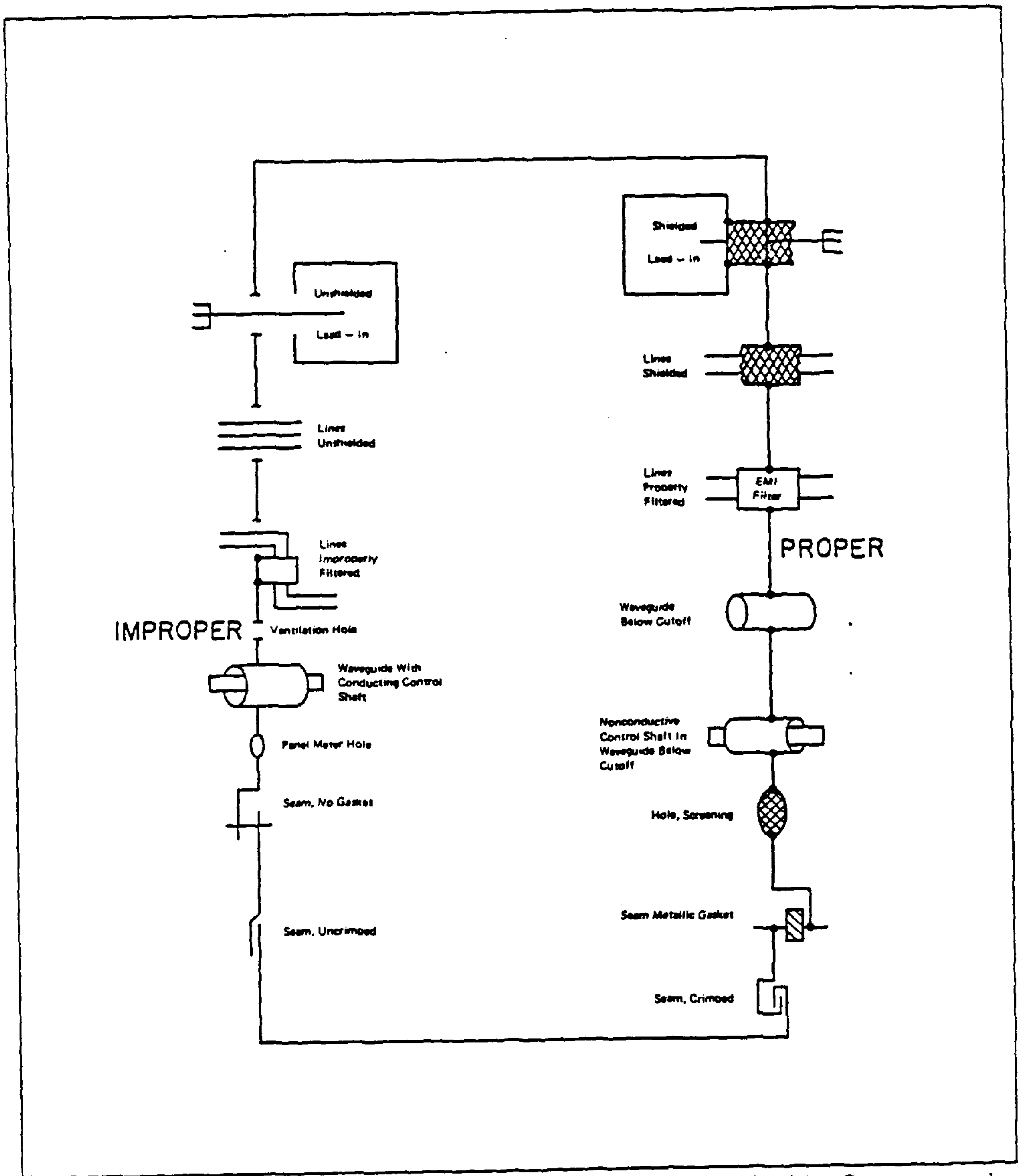


Figure 30. Typical Shielding: Compartment Discontinuities-Proper and Improper. [Ref. 17: p. 33]

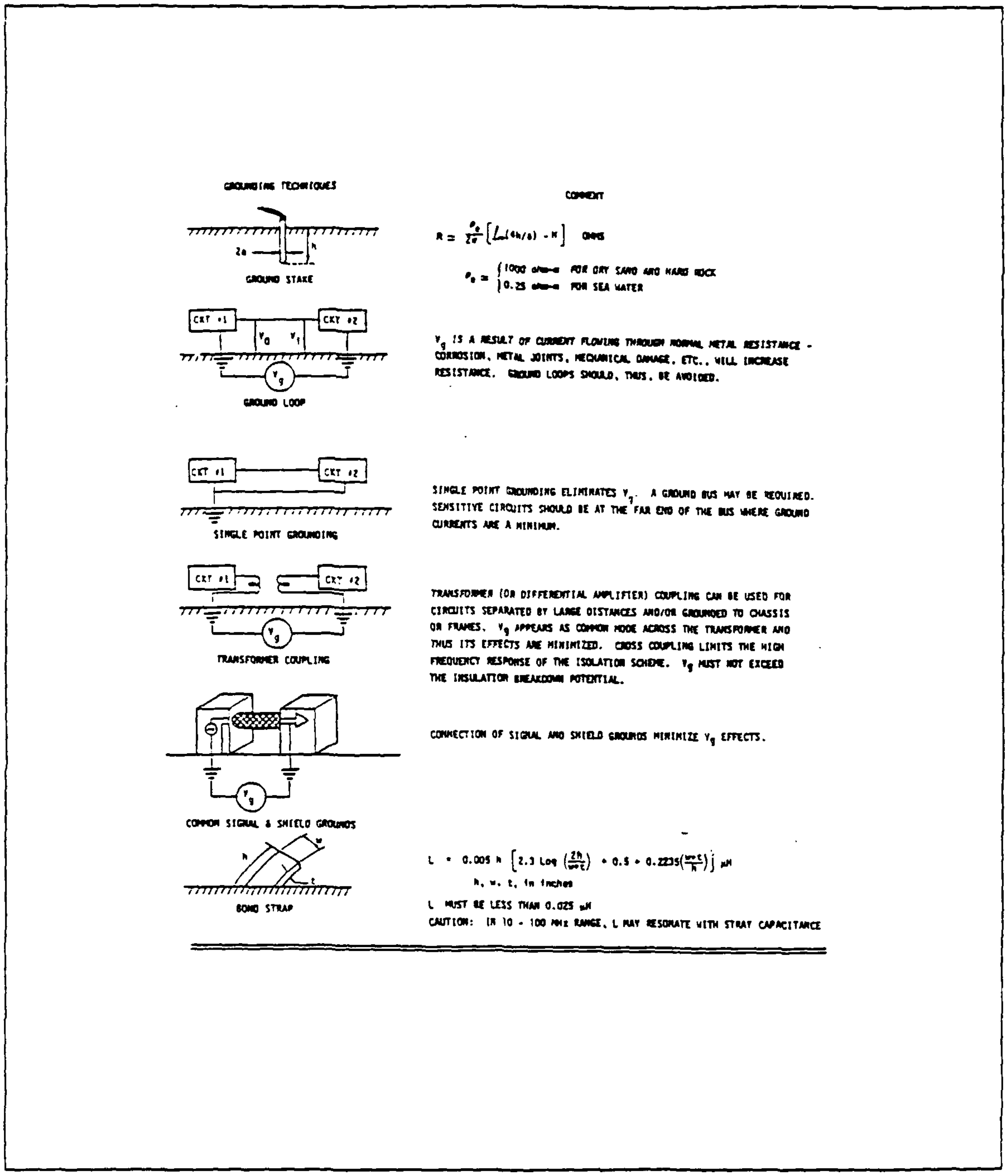


Figure 31. Grounding Techniques: [Ref. 39: p. 65-14]

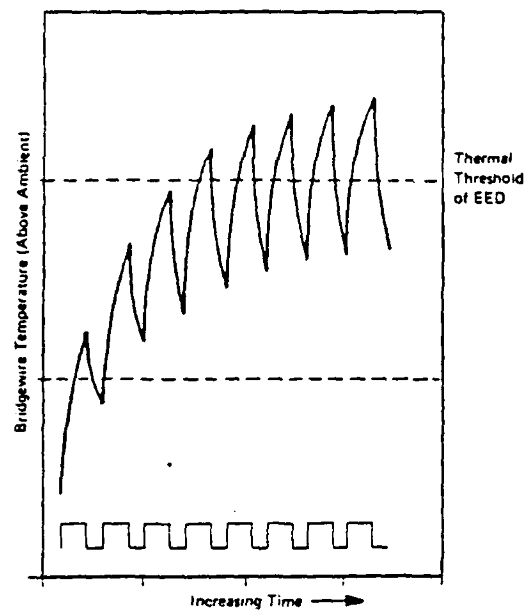


Figure 32. Temperature Increases Due to Thermal Stacking: [Ref. 17: p. 19]

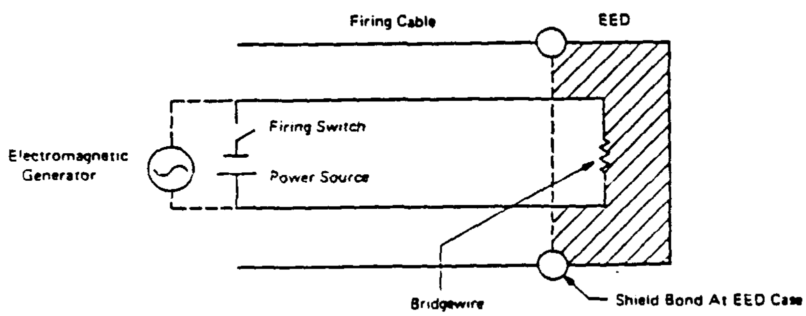


Figure 33. Differential Mode of RF Excitation in a Two Wire Firing System: [Ref. 17: p. 19]

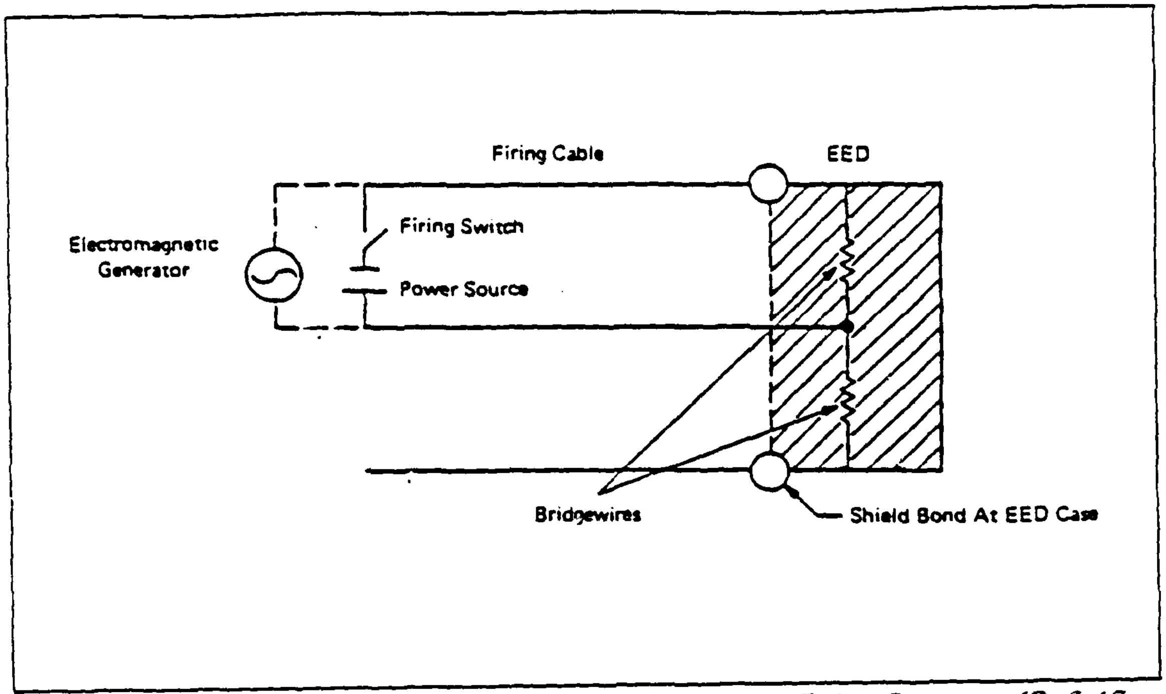


Figure 34. Coaxial Mode of RF Excitation in a Coaxial Firing System: [Ref. 17: p. 19]

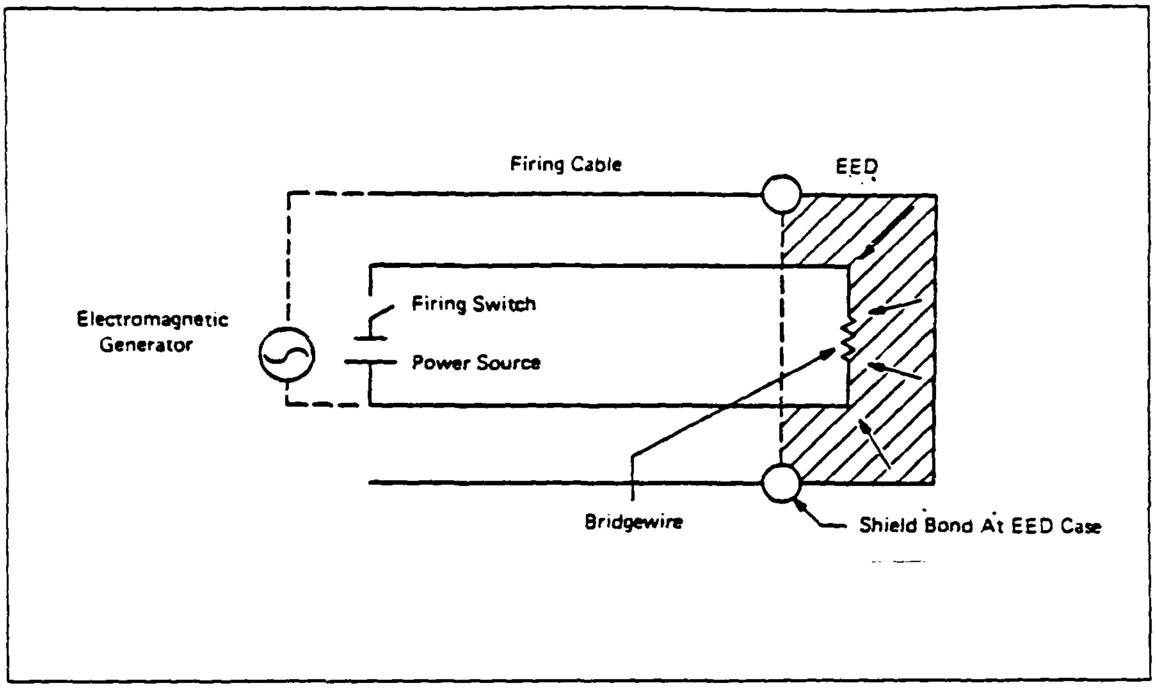


Figure 35. Coaxial Mode of RF Excitation in Two Wire Firing System: [Ref. 17: p. 19]

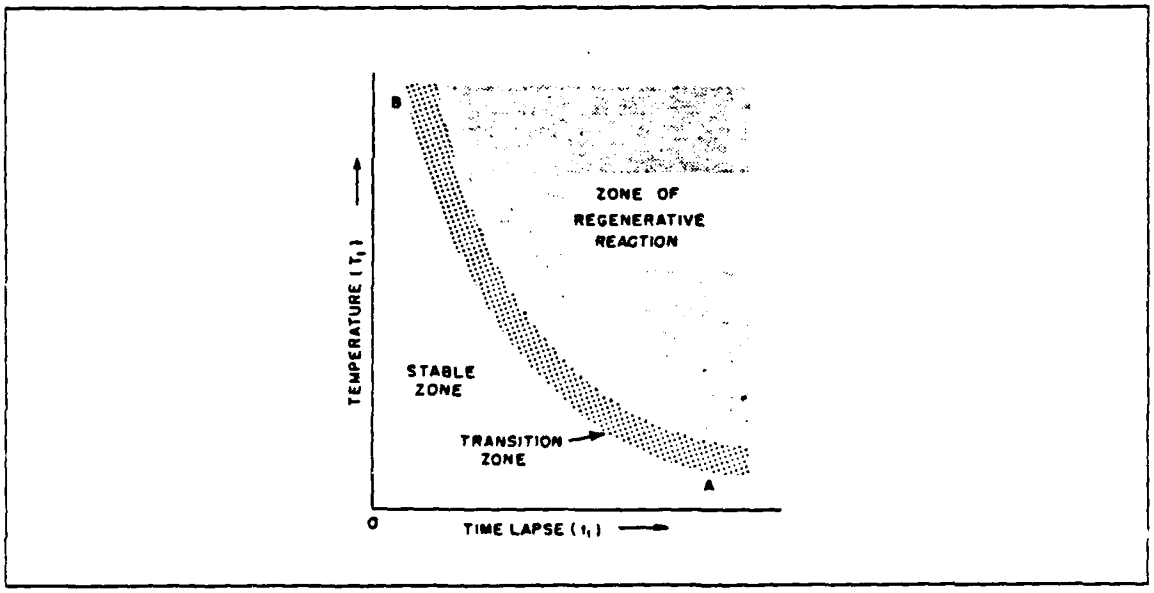


Figure 36. Temperature Versus Time Explosive Relationship: Chart Showing Temperature Versus Time Relationship Governing Typical Explosive Reaction [Ref. 28: p. 2-1]

*Calculation of MNFC if the recorder detects a current:
Information- 1000 mA MNFC of EED
Available power = 30 mW/cm^2
Recorder Sensitivity = 20 mA
Required Environment = 100 mW/cm^2 frequency
Response- Recorder reading = 50 mA

Calculation- 50 mA/1000 mA = 0.05x 100 = 5% MNFC

*Calculation of MNFC if the recorder does not detect a current:
Information- same as above
Response- none

Calculation- $\sqrt{\frac{100mW/cm^2}{30mW/cm^2}}\,x20mA = 36.5mA$

- 36.5 mA/1000 x 100 = 3.6% MNFC

Figure 37. Calculation of Test Results: [Ref. 15]

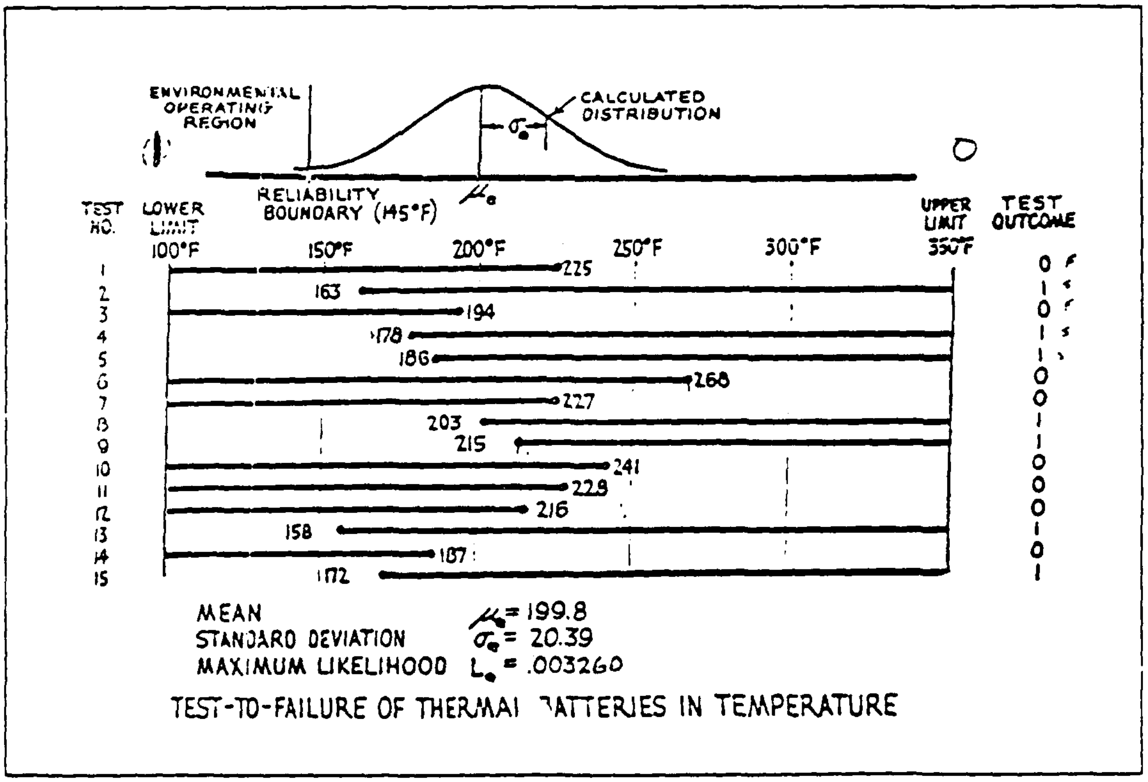


Figure 38. Sample One-Shot Test: [Ref. 30]

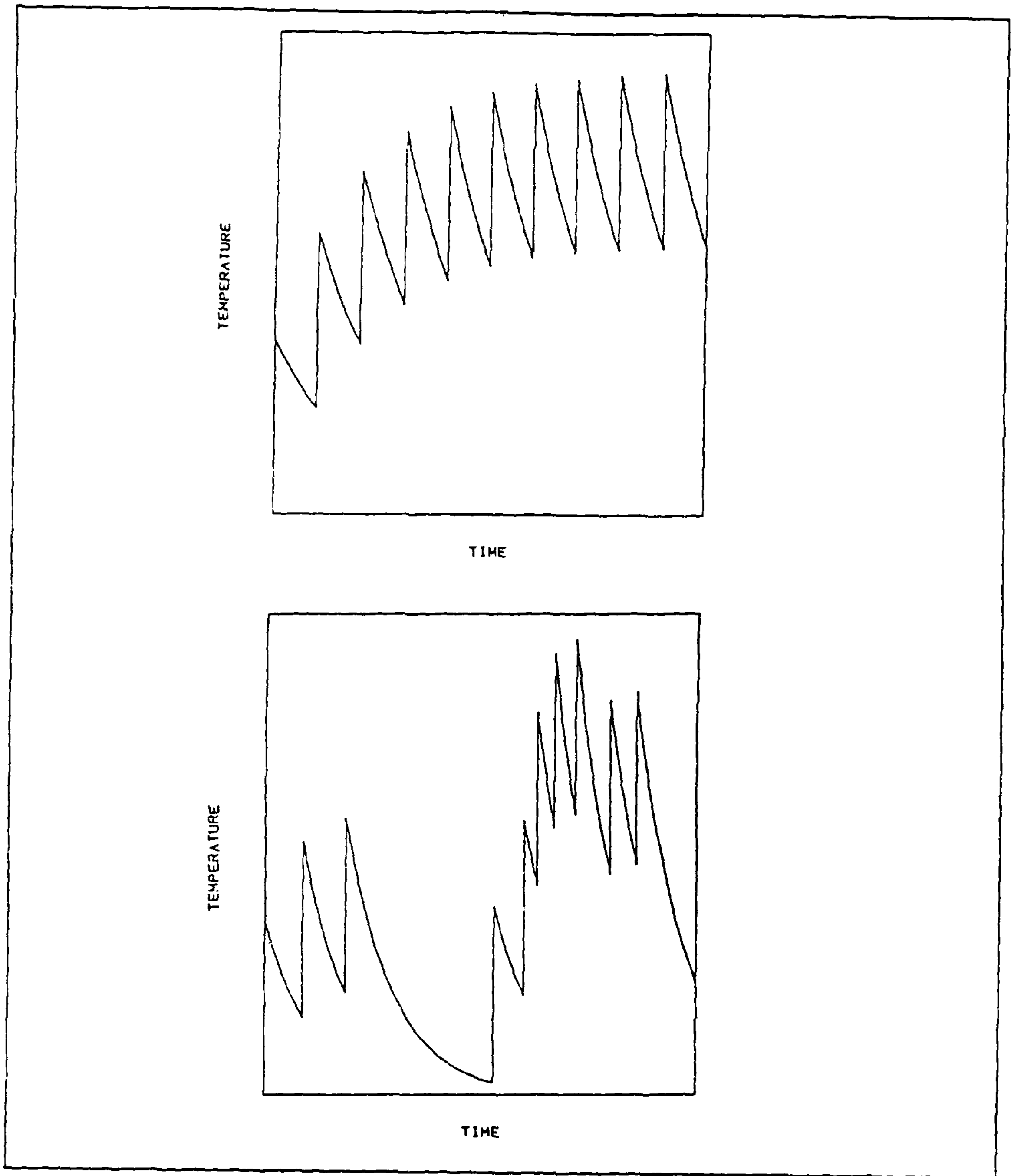


Figure 39. Illustration of the Cumulative Heating (Stacking) of an EED: [Ref. 32]

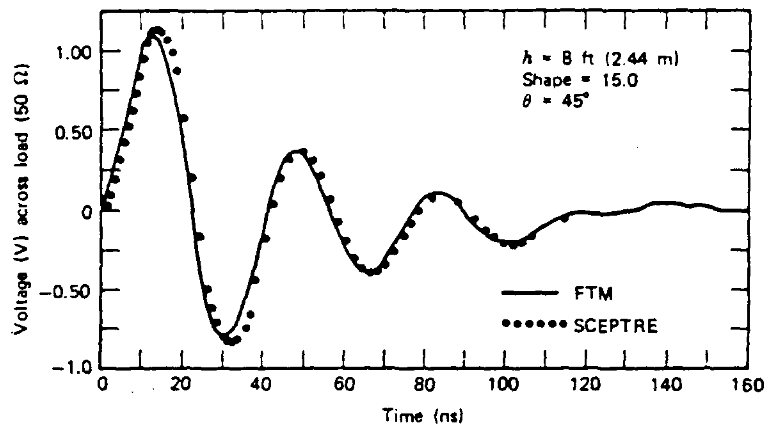


Figure 40. FTM Versus SCEPTRE for Monopole Antenna with 50-Ω Load: [Ref. 2: p. 52]

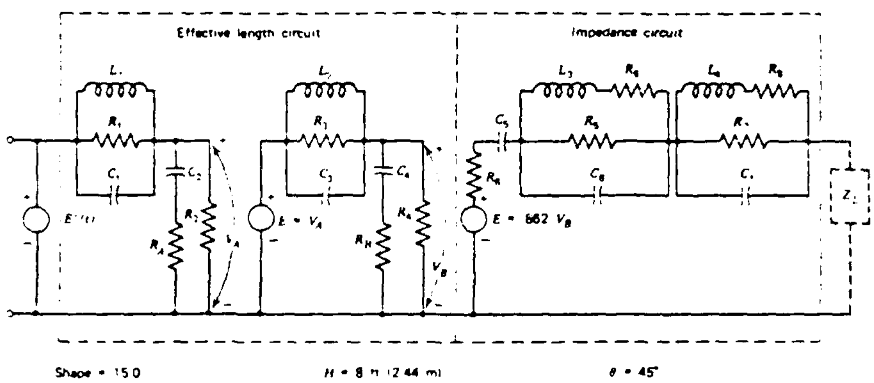


Figure 41. Monopole Antenna Equivalent Circuit: [Ref. 2: p. 52]

A.LOW-PASS FRACTION

$$F_{low}(\omega_1) = \frac{I(\omega_1)}{I(\infty)} = \frac{1}{\pi b}\left[(a+b)\tan^{-1}\left(\frac{\omega_1}{a-b}\right) - (a-b)\tan^{-1}\left(\frac{\omega_1}{a+b}\right)\right] \quad (121)$$

B.HIGH-PASS FRACTION (above a lowest limit ω_2)

$$F_{high} = 1 - F_{low}(\omega_2) \quad (122)$$

when $\omega_2 >> (a-b)$ or $(a+b)$. If the arc tangent is approximated as:

$$\tan^{-1}(x) \simeq \left(\frac{1}{x}\right) - \left(\frac{1}{x^3}\right) \quad (123)$$

then

$$F_{high} \simeq \frac{4a(a^2-b^2)}{3\pi\omega_2^3} \quad (124)$$

C.BAND-PASS FRACTION

$$F_{band}(\omega, \Delta\omega) = F_{low}(\omega + \Delta\omega) - F_{low}(\omega). \quad (125)$$

When $\Delta\omega << \omega$:

$$F_{band}(\omega, \Delta\omega) \simeq \Delta\omega \frac{d[F_{low}(\omega)]}{d\omega} \simeq \frac{4a(a^2-b^2)}{\pi\omega^3}\left[\frac{\Delta\omega}{\omega}\right] \quad (126)$$

Figure 42. Antenna Filter Equations: [Ref. 34]

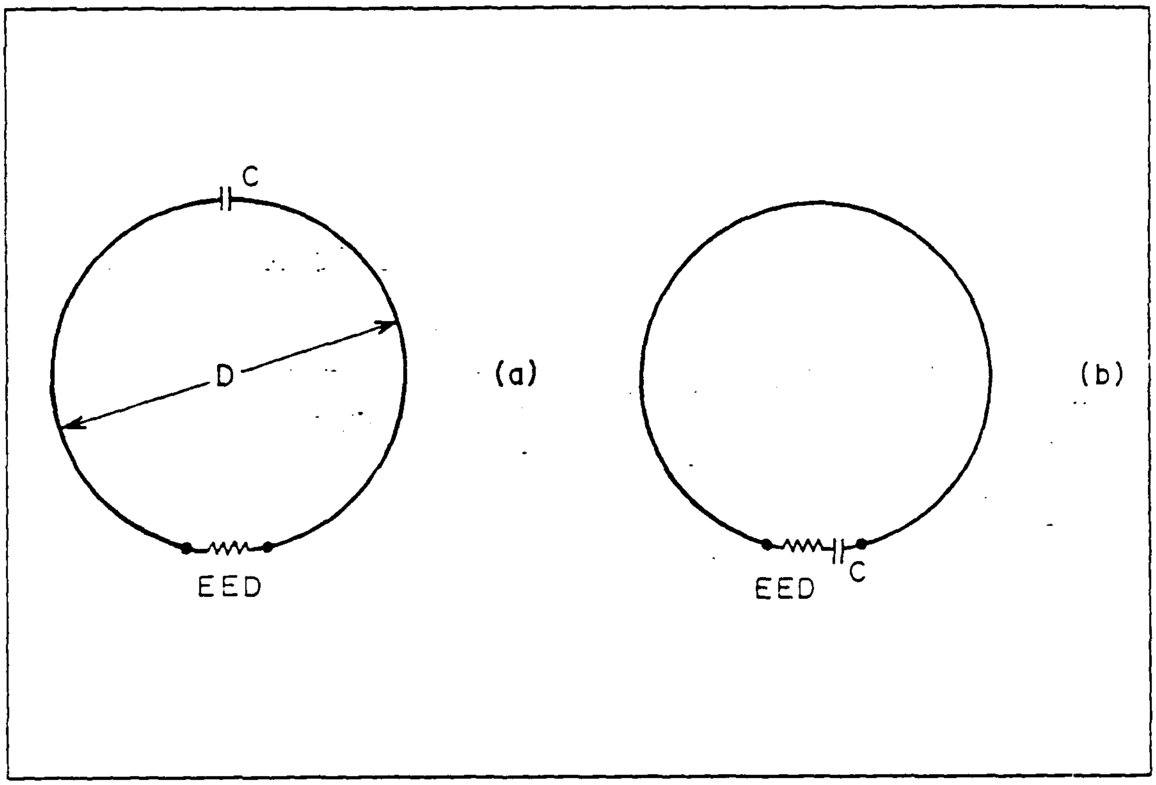


Figure 43. **Loop Antenna with Tuning Capacitor:** [Ref. 35]

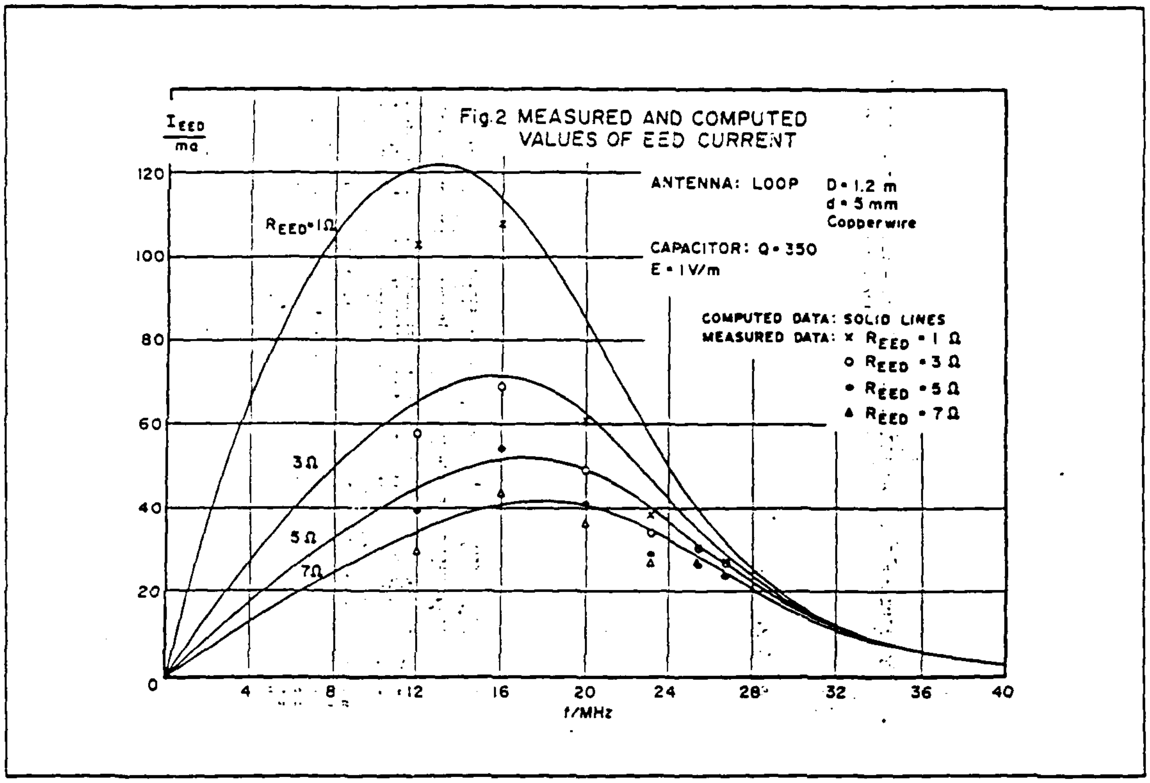


Figure 44. Measured and Computed Values of EED Current: [Ref. 35]

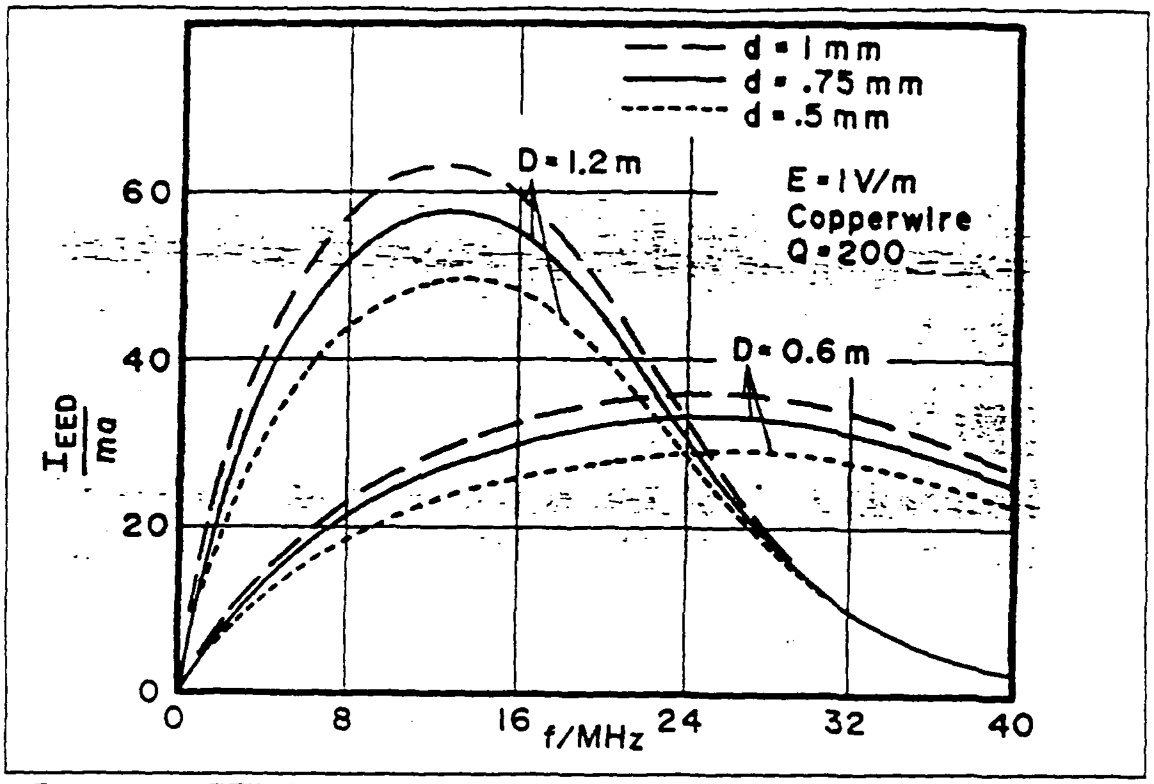


Figure 45. EED Current for Loop Antennas and $R_{EED} = 1\Omega$: [Ref. 35]

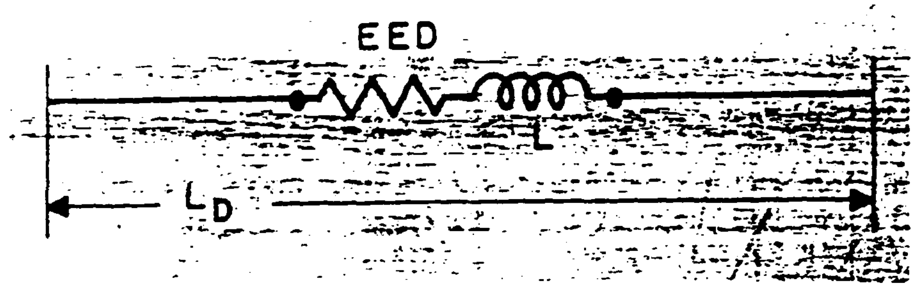


Figure 46. Dipole Configuration: [Ref. 35]

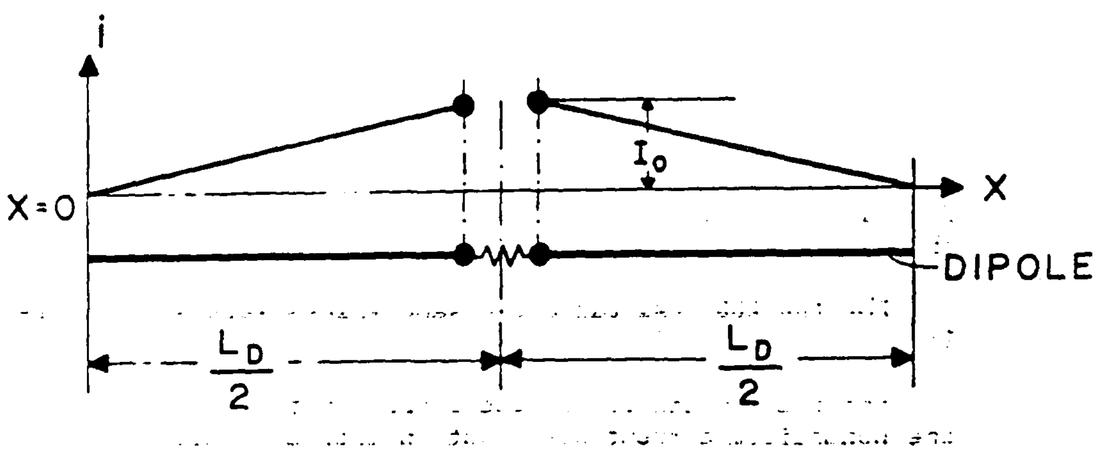


Figure 47. Current Distribution on Dipole: [Ref. 35]

EMP	HERO
↓ ↑	↓
High Altitude Burst	CW or Phased Array RADAR
↓ ↑	↓
EMP Generated	Electromagnetic Radiation Present
↓ ↑	↓
Current Induced	Current Induced
↓ ↑	↓

⇒ ⇐ *Current Causes Ohmic Heating* ⇐

Figure 48. Flowchart of EMP/HERO Comparison

HERO

Equation used:

$$\theta_{\max} = \frac{I^2 R_e}{\gamma - I^2 R\alpha} = \frac{I^2 R_e}{\gamma'} . \tag{127}$$

value for mean current of 0.259 amps θ_{max} = 122 °C
value for max current of 0.300 amps θ_{max} = 170 °C
value needed for current of 0.520 amps θ_{max} = 705 °C

EMP

Equation used:

$$\theta = \left[\frac{I^2 R}{\gamma - I^2 R\alpha} \right] \left[\frac{t}{\tau} \right] = \frac{I^2 R t}{C_P} . \tag{128}$$

where
t = 10 x 10^{-9} seconds

$C_P = 2.4$ *microjoules/* °C

R = 0.2 ohms

Value for mean current of 374.4 amps θ = 112°C
Value for max current of 500.0 amps θ = 208°C
Value needed for current of 900.0 amps θ = 675°C

Figure 49. Example of Current to Temperature Transfer Function

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